

Cupola melting of cast iron in iron foundries



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CUPOLA MELTING OF CAST IRON IN IRON FOUNDRIES

This Guide is No. 58 (revised) in the Good Practice Guide series. It provides advice on practical ways of improving the energy efficiency of cupola melting in iron foundries. It considers the various factors that affect the efficiency of cupola operation, and examines the practices that can be implemented to improve current performance. Attention is also given to environmental and safety considerations.

Checklists give the reader a quick reference to the main areas in which efficiency can be improved.

Prepared for the Department of the Environment, Transport and the Regions by:

ETSU
Harwell
Didcot
Oxfordshire
OX11 0RA

and

The Castings Development Centre
Alvechurch
Birmingham
B48 7QB

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Energy Efficiency Enquiries Bureau
ETSU
Harwell
Didcot
Oxfordshire
OX11 0RA

Tel No: 01235 436747. Fax No: 01235 433066. E-mail: etsuenq@aeat.co.uk

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FOREWORD

This Guide is part of a series produced by the Government under the Energy Efficiency Best Practice Programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

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ENGLAND

London

Govt Office for London
6th Floor
Riverwalk House
157-161 Millbank
London
SW1P 4RR
Tel 020 7217 3435

East Midlands

The Sustainable Development Team
Govt Office for the East Midlands
The Belgrave Centre
Stanley Place
Talbot Street
Nottingham
NG1 5GG
Tel 0115 971 2476

North East

Sustainability and Environment Team
Govt Office for the North East
Wellbar House
Gallowgate
Newcastle-upon-Tyne
NE1 4TD
Tel 0191 202 3614

North West

Environment Team
Govt Office for the North West
Cunard Building
Pier Head
Water Street
Liverpool
L3 1QB
Tel 0151 224 6401

South East

Sustainable Development Team
Govt Office for the South East
Bridge House
1 Walnut Tree Close
Guildford
Surrey
GU1 4GA
Tel 01483 882532

East

Sustainable Development Awareness Team
Govt Office for the East of England
Heron House
49-53 Goldington Road
Bedford
MK40 3LL
Tel 01234 796194

South West

Environment and Energy Management Team
Govt Office for the South West
The Pithay
Bristol
Avon
BS1 2PB
Tel 0117 900 1700

West Midlands

Regional Sustainability Team
77 Paradise Circus
Queensway
Birmingham
B1 2DT
Tel 0121 212 5300

Yorkshire and the Humber

Sustainable Development Unit
Govt Office for Yorks and the Humber
PO Box 213
City House
New Station Street
Leeds
LS1 4US
Tel 0113 283 6376

NORTHERN IRELAND

IRTU Scientific Services
17 Antrim Road
Lisburn
Co Antrim
BT28 3AL
Tel 028 9262 3000

SCOTLAND

Energy Efficiency Office
Enterprise and Lifelong Learning Dept
2nd Floor
Meridian Court
5 Cadogan Street
Glasgow
G2 6AT
Tel 0141 242 5835

WALES

Business and Environment Branch
National Assembly for Wales
Cathays Park
Cardiff
CF10 3NQ
Tel 029 2082 5172

SUMMARY

Despite competition from electric melting and increasing environmental legislation, particularly regarding emission levels, the cupola remains a traditional workhorse in UK iron foundries. As such, it is widely employed for the production of flake, nodular, malleable and low alloy iron castings.

There are currently some 200 ferrous foundry sites in the UK producing 1.35 Mt of finished castings annually, of which 700 kt are flake and 650 kt nodular iron. The iron sector consumes 29 PJ/year of energy at a cost of £104 M. Coke remains the major source of energy in iron foundries. A survey carried out for the Energy Efficiency Best Practice Programme, reported in Energy Consumption Guide 48, indicated that this represented £42 M, or 41% of direct energy consumption. In comparison, the consumption of electricity for the same sector represented £36.4 M, or 35% of supplied energy, whilst accounting for 57% of primary energy used, taking into account the conversion factor of primary:delivered energy at the power station. It should also be remembered that in addition to providing energy for melting, coke also yields some of its fixed carbon to the resulting iron, thus reducing the requirement for re-carburisation which is necessary in electric melting.

The apparently simple nature of cupola furnace operation disguises the complex physical changes and chemical reactions which occur. Some operators of such plant fail to recognise the importance that sound furnace design and correct set-up have in establishing optimum melting conditions, thereby promoting good metallurgical control, i.e. chemical composition and metal temperature.

This Guide firstly identifies the main aspects of furnace design and their influence in obtaining correct combustion conditions within the melting unit. Secondly, recommendations are made concerning best practices in operational control to maximise performance. Reference is made to safety considerations and the need for environmental controls, the latter to meet requirements of the Environmental Protection Act 1990 and its associated Process Guidance Notes.

An outline is provided of the various external treatment processes, used on occasion as adjuncts to the cupola melting operation; principally involving carburisation and desulphurisation, before finally describing recent developments in cupola melting practice.

It is estimated that by adopting best practices and through attention to detail, many foundries employing cupola melting could reduce coke consumption by as much as 20%, providing energy cost savings, improved productivity and reduced emissions.

CONTENTS

Section		Page No.
1.	INTRODUCTION	1
1.1	Background	1
1.1.1	The UK Ferrous Foundry Industry	1
1.1.2	Iron Foundry Melting Facilities	1
1.2	The Purpose of this Guide	2
2.	THE CUPOLA FURNACE	3
3.	DESIGN CONSIDERATIONS	5
3.1	Overview	5
3.2	Blast Rates	5
3.3	Tuyères	6
3.4	Diameter of Melting Zone	8
3.5	External Shell Diameter	8
3.6	Shaft Height	8
3.7	Well Depth	9
3.7.1	Intermittently Tapped Cupolas	9
3.7.2	Continuously Tapped Cupolas	10
3.8	Cupola Linings	10
3.8.1	Lining Materials	10
3.8.2	Water Cooling	10
3.8.3	Liningless Operation	11
3.9	Divided Blast Cupola	12
3.10	Oxygen Use in Cold Blast Cupola Operation	14
3.11	Hot Blast Operation	16
3.12	Continuous Tapping Systems	17
3.12.1	Continuous Front Tapping and Slagging	18
3.12.2	Continuous Front Tapping and Rear/Side Slagging	18
3.12.3	Siphon Brick Tapping System	19
3.13	Slag Handling and Uses	20
4.	OPERATIONAL CONTROL	22
4.1	Overview	22
4.2	Blast Rate Measurement and Control	22
4.3	Charge Materials	24
4.3.1	Metallics	24
4.3.2	Coke Quality	26
4.4	Coke Bed Preparation	27
4.5	Lining Practice	28
4.5.1	Lining Problems and the Need for Repair	28
4.5.2	Lining Repair Techniques	29
4.6	Fluxing Practice	30
4.6.1	Flux Requirements for Acid-lined Cupolas	30
4.6.2	The Importance of Correct Flux Addition	31
4.6.3	Flux Addition to the Coke Bed	31
4.6.4	Supplementary Fluxes in Acid Slag Operation	31
4.7	Materials Handling and Cupola Charging Systems	31
4.7.1	Materials Handling	31
4.7.2	Cupola Charging Systems	31
4.8	Metal Distribution	32

Section	Page No.	
5.	EXTERNAL TREATMENTS AS AN AID TO EFFICIENT CUPOLA MELTING	34
5.1	Background	34
5.2	Metal Treatment Processes	34
5.2.1	Tuyère Injection	34
5.2.2	Porous Plug Ladle	35
5.2.3	Shaking Ladle	36
6.	ENVIRONMENTAL CONTROLS	37
6.1	Background	37
6.2	Statutory Requirements	37
6.2.1	Environmental Protection Act	37
6.2.2	Integrated Pollution Prevention and Control (IPPC)	38
6.3	Designing Cupolas for Effective Environmental Operation: The Problems	39
6.4	Fume Cleaning Options	39
6.4.1	Dry Filtration	39
6.4.2	Wet Scrubbing	40
6.4.3	Hot Blast Cupola Operation	40
6.5	Energy Efficient Environmental Control	41
7.	SPECIALISED CUPOLA OPERATING TECHNIQUES	42
7.1	Supersonic Oxygen Injection	42
7.2	Cokeless Cupola Operation	43
7.3	Dust and Waste Injection Systems	44
7.4	Blast Superheating from Auxiliary Energy Sources	45
8.	SAFETY CONSIDERATIONS	47
8.1	Risks Associated with Carbon Monoxide	47
8.2	Explosion Risks	47
8.3	Securing Cupola Drop-bottom Doors	48
8.4	The Cupola Drop	48
8.5	Fettling the Cupola	48
8.6	Oxygen Use	49
8.7	Charging Systems	49
9.	MINIMISING COKE CONSUMPTION: AN ACTION CHECKLIST	50

FIGURES

Fig 1	Schematic of cold blast cupola	3
Fig 2	Typical cupola net diagram	6
Fig 3	Influence of cupola diameter on well capacity	9
Fig 4	Heat losses through the cupola shell	11
Fig 5	Schematic of hot blast cupola	12
Fig 6	Schematic of divided blast cupola	13
Fig 7	Oxygen enrichment and injection	15
Fig 8	Effect of blast pre-heating on furnace efficiency	16
Fig 9	Continuous front tapping and slagging	18
Fig 10	Continuous front tapping and rear slagging	18
Fig 11	Siphon brick tapping	19
Fig 12	Air weight control system	22
Fig 13	Influence of intermittent blowing on metal temperature	23
Fig 14	The effect of coke size on metal temperature	27
Fig 15	Lining repair techniques	29
Fig 16	Tuyère injection for metal treatment	35
Fig 17	Supersonic oxygen injection	43
Fig 18	Duplexing with a cokeless cupola	44
Fig 19	The plasma torch	46
Fig 20	Reducing explosion risks during blast-off periods	47

TABLES

Table 1	Cupola design data	7
Table 2	Requisite shaft heights for cupolas	8
Table 3	Effect of charge materials on casting quality	25

1. INTRODUCTION

1.1 **Background**

1.1.1 *The UK Ferrous Foundry Industry*

There are currently 200 ferrous foundry sites in the UK. These produce more than 1.3 million tonnes of finished castings per year, almost equally divided between flake iron (0.7 million tonnes) and nodular iron (0.65 million tonnes). Small quantities of malleable and low alloy castings are also produced.

The iron sector consumes 29 petajoules (PJ) of energy per year worth £104 million.

Coke remains the main source of iron foundry energy. A survey carried out for the Energy Efficiency Best Practice Programme and summarised in Energy Consumption Guide 48 (March 1985) indicated that coke accounted for 41% of direct energy consumption, with a value of £42 million. As well as providing energy for melting, coke also yields some of its fixed carbon to the resulting iron, thereby reducing the need for recarburisation. The same survey showed that electricity accounted for 35% of delivered energy (57% of primary energy), valued at £36.4 million. Where iron is melted electrically, recarburisation is subsequently required.

1.1.2 *Iron Foundry Melting Facilities*

The ability of the cupola to melt many types of metallic iron charge material reliably and over a wide range of melting rates meant that, until the 1950s, the cupola was the primary facility for molten metal supply in most UK iron foundries.

Many smaller iron foundries – and some higher-output units – have since abandoned cupola melting in favour of electric induction furnaces. These have obvious operational advantages for small and medium-sized foundries with a variable demand for molten metal encompassing a range of grades and alloys. However, the cupola can still be the most cost-effective and energy efficient melting facility in larger foundries producing grey and ductile iron castings. Estimates suggest that at least 100 UK foundries still use cupolas, with at least 60 using them as their only source of molten metal. The remainder combine cupola and electric furnace melting.

Most cupola melting plant is based on conventional cold blast operation, and there has been little overall change in basic operating procedures. However, many foundries have included improvements such as divided blast and hot blast operation, automatic blast control, oxygen enrichment and better charge weighing practices.

The requirements of the Environmental Protection Act (1990) have now compelled most foundries to review their melting practices and procedures. Meeting particulate emission limits for cold blast cupolas became mandatory in 1997, and several of the larger foundries have responded by installing new cupola melting systems that incorporate updated technology. Cost-effective developments in this field include cokeless and low-fume cupolas, long-campaign furnaces and supersonic oxygen injection. Other foundries have decided to uprate existing systems rather than re-equip in this way.

1.2 Purpose of this Guide

The apparently simple nature of cupola furnace operation disguises the complex physical changes and chemical reactions that occur. As a result, plant operators sometimes fail to recognise the importance of sound furnace design and correct set-up in establishing the optimum melting conditions that will ensure the correct chemical composition and temperature of the metal.

Estimates suggest that, by adopting best practice and paying attention to detail, cupola operators can reduce their coke consumption by as much as 20%, thereby achieving significant cost savings, improved productivity and reduced emissions.

The purpose of this Guide is to indicate where the opportunities for improvement exist. Section 3 identifies the main aspects of furnace design and outlines how they influence correct combustion within the melting unit. Section 4 focuses on operational best practice for maximising cupola performance. Section 5 examines the role of external treatments in efficient cupola melting. Environmental controls and their implications for cupola melting are the subject of Section 6, while Section 7 examines some of the new techniques that have been developed to meet environmental requirements. Section 8 summarises some of the safety issues involved.

2. THE CUPOLA FURNACE

The cupola is essentially a shaft furnace into which is charged:

- the metal to be melted;
- metallurgical coke (the fuel);
- a fluxing material such as limestone.

The metal normally comprises steel scrap, foundry return (and bought-in) cast iron scrap and pig iron. Pig iron content is kept to a minimum (0 - 20%) because it is considerably more expensive than the other metal sources.

Combustion air is blown into the furnace through radially disposed tuyères located towards the bottom of the shaft (Fig 1). Coke combustion generates hot gases, which rise, heating and melting the descending metal charges. There are three principal types of cupola operating in the UK:

- cold blast cupolas with a single row of tuyères;
- divided cold blast cupolas with two rows of tuyères;
- hot blast cupolas with one or two rows of tuyères in which the combustion air is pre-heated, typically to about 500°C.

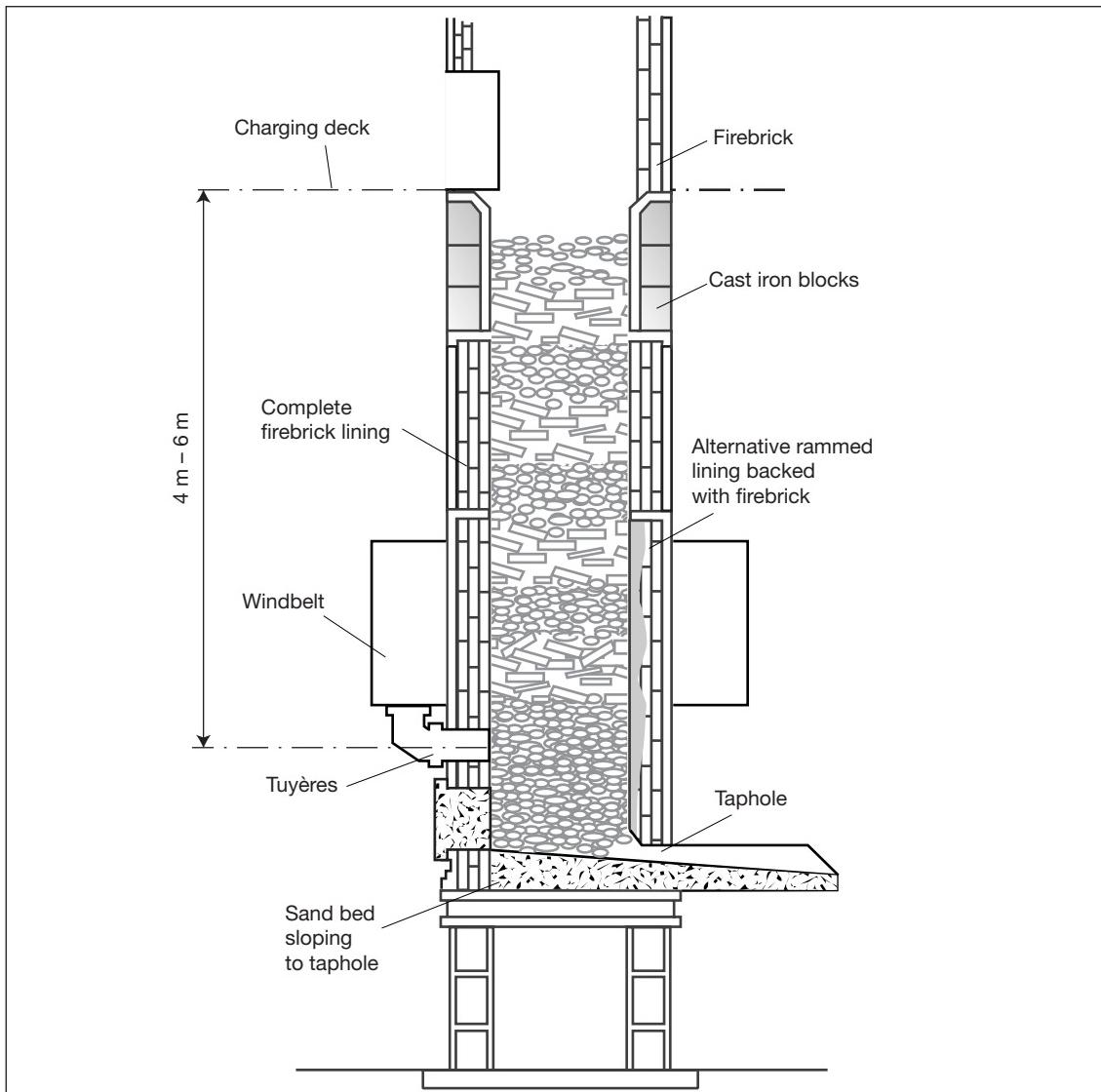


Fig 1 Schematic of cold blast cupola

Modifications can be made to cupola operation to increase efficiency. Examples include:

- adding oxygen to the combustion air;
- operating with continuous metal tapping and slagging systems;
- the use of water cooling and liningless systems for long melting campaigns.

The coke and metallic charge materials are fed into the cupola through a high-level opening in the shaft, and move down the shaft as melting progresses. Melting starts when pieces of solid charge reach the bed level, approximately one metre above the tuyères. Fusion of the charge results in droplets of molten iron falling through the incandescent coke bed and becoming superheated. Intimate contact between the molten iron and coke occurs, resulting in carbon pick-up by the metal.

3. DESIGN CONSIDERATIONS

3.1 Overview

Energy efficiency in cupola melting is maximised by optimising the degree of combustion between oxygen in the air blast and the charge coke. It is also influenced by the uniformity of air distribution from the tuyères and, in this respect, the development of the divided blast cupola has proved extremely beneficial.

Melting rate, chemical composition and metal temperature depend on fundamental cupola design factors. The widespread use of oxygen enrichment of the blast air, either continuously or for the rapid recovery of metal temperature and melting rate following a blast-off period, has contributed to improved efficiency. The use of hot blast cupola operation, in which the blast air is pre-heated to approximately 550°C, also markedly improves thermal and, therefore, energy efficiency.

3.2 Blast Rates

The rate at which cast iron is melted in a cupola depends on the volume of combustion air blown into the furnace (the blast rate) and on the quantity of coke charged. For any given cupola, the influence of the blast rate and the coke charge on melting rate and metal tapping temperature can be expressed in the form of a net diagram. However, a net diagram is only valid for the cupola for which it was derived. It cannot be used to predict the tapping temperature of the metal for any other cupola, because this will depend on that cupola's specific design and operational factors.

Fig 2 shows a net diagram for an intermittently tapped cold blast cupola 760 mm (30.4 in) in diameter. It illustrates the following:

- For a fixed quantity of coke carbon burnt per 100 kg of iron melted (i.e. for a constant coke charge), an increase in the blast rate increases both the melting rate and the metal temperature until a maximum is reached: thereafter, any further increase in the blast rate causes the metal temperature to fall, although the melting rate continues to increase.
- For a given (constant) blast rate, any increase in the quantity of coke charged reduces the melting rate and increases the metal temperature.
- To increase the metal temperature but maintain a constant melting rate, it is necessary to increase both the blast rate and the coke charge at the same time.
- For a constant coke charge there is an optimum blast rate and a corresponding melting rate at which a maximum metal tapping temperature is obtained. The optimum blast rate increases, and the optimum melting rate falls, as the coke charge is increased.

Fig 2 clearly demonstrates the desirability of operating at the optimum blast rate, thereby minimising the quantities of coke that are consistent with maintaining a given tapping temperature:

- A metal tapping temperature of 1,450°C can be obtained using a coke charge equivalent to 14 kg of carbon per 100 kg of iron and a blast rate of 84 m³/minute per m² (274 ft³/minute per ft²) of melting zone area. The specific melting rate under these conditions is 5.6 tonnes/m² per hour (0.51 tonnes/ft² per hour).
- The same tapping temperature can be achieved using a coke charge equivalent to 10.5 kg of carbon per 100 kg of iron, and a blast rate of 108 m³/minute per m² of melting zone area. The specific melting rate under these conditions is 9.1 tonnes/m² per hour. This represents optimum operating conditions.

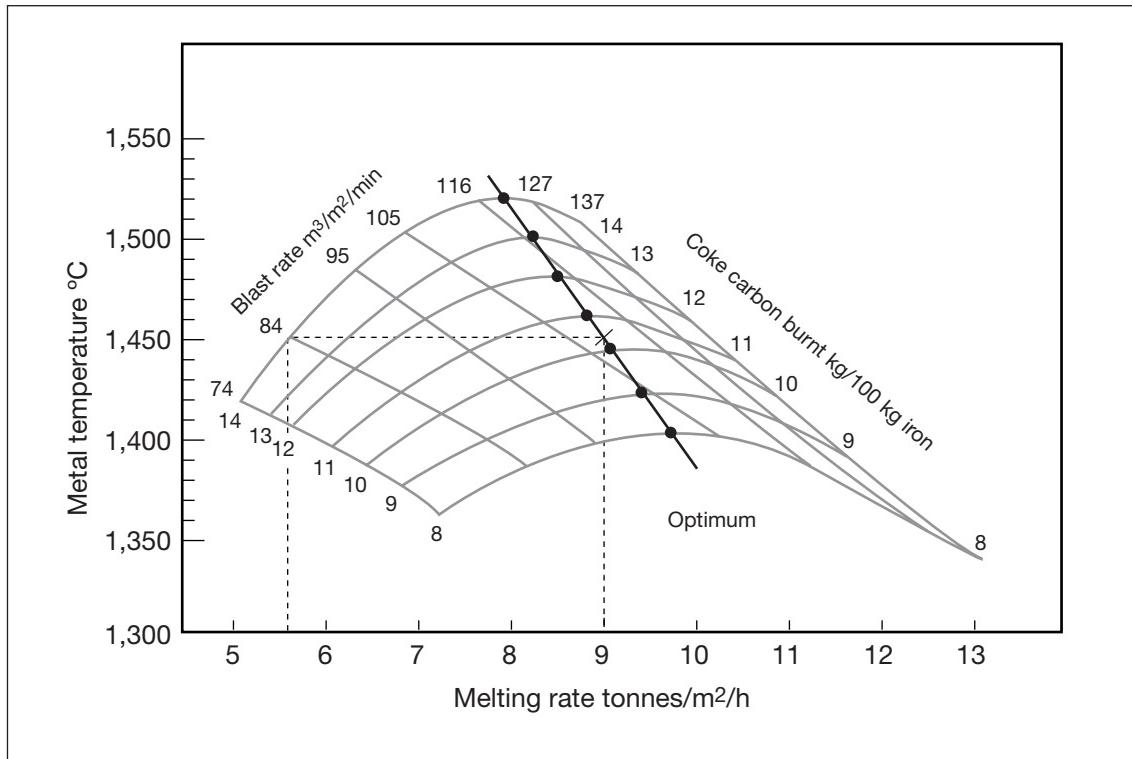


Fig 2 Typical cupola net diagram

A further advantage of operating at, or close to, the optimum is the fact that the variation in metal temperature with blast rate for a constant coke charge is flatter. The cupola will therefore be less sensitive to unavoidable variations in blast rate.

In practice, the optimum blast rate varies with the metal:coke ratio and the nature of the materials melted. However, this rate has been established, both experimentally and practically, at approximately 115 m³/minute per m² of cupola cross-sectional area at the level of the tuyères.

Table 1 shows summarised cupola data and gives the optimum blast rate for cupolas of varying cross-sectional area and diameter.

3.3 Tuyères

The function of the tuyères is to produce uniform combustion conditions throughout the coke bed by conducting equal quantities of air from the windbelt into the cupola through each tuyère unit. Tuyère size has little effect on the melting behaviour of a cold blast cupola, as long as the blast rate and the air distribution to each tuyère are reasonably uniform. However, the total area of the tuyères is generally recommended to be between one quarter and one seventh of the cross-sectional area of the internal diameter of the cupola. This should ensure that:

- the tuyères are sufficiently large to prevent any serious loss of pressure through them and to minimise any throttling effect on the blower;
- sufficient surplus area is available to allow one or more of the tuyères to be reduced in area to correct poor blast distribution (indicated by repeated uneven burn-out of the lining).

Although not critical, the number of tuyères used in a cupola should increase with furnace diameter, thereby improving uniformity of air supply.

Table 1 Cupola design data

1 Approximate melting rate at various metal:coke ratios under steady operating conditions, t/h,ton/h	2 Recommended blowing rate* m ³ /min	3 Cross-sectional area of melting zone ft ²	4 Diameter of melting zone cm	5 Recommended blower capacity† ft ³ /min			6 Approximate well capacity m ³ /min	7 Total tuyère area in w.g. cm ²	8 Number of tuyères	9 Approximate bed weight cwt per ft height
				Volume	Discharge pressure kPa	t per m height				
10:1 Metal:coke ratio	8:1	6:1	m ³ /min	ft ³ /min	m ²	ft ²	cm	in	m ³ /min	ft ³ /min
1.6	1.3	1.1	18.5	665	0.16	1.77	45	18	22	800
2.2	1.9	1.5	25.5	900	0.22	2.40	52.5	21	30	1080
2.9	2.5	1.9	32.0	1180	0.28	3.14	60	24	40	1420
3.7	3.1	2.5	41.5	1495	0.36	3.98	67.5	27	50	1800
4.5	3.9	3.1	50.5	1840	0.44	4.91	75	30	60	2200
5.5	4.7	3.7	61.0	2230	0.53	5.94	82.5	33	75	2680
6.6	5.6	4.4	73.5	2650	0.64	7.07	90	36	90	3180
7.7	6.5	5.2	86.5	3110	0.75	8.30	97.5	39	105	3740
9.0	7.6	6.1	100.0	3620	0.87	9.64	105	42	120	4350
10.3	8.7	6.9	115.0	4140	1.00	11.04	112.5	45	140	4970
11.7	10.0	7.9	130.0	4720	1.13	12.57	120	48	155	5660
13.2	11.2	8.9	145.0	5300	1.28	14.19	127.5	51	175	6360
14.8	12.6	10.0	165.0	5950	1.43	15.90	135	54	200	7140
16.5	14.0	11.2	185.0	6650	1.60	17.72	142.5	57	220	7980
18.3	15.6	12.4	205.0	7360	1.77	19.63	150	60	250	8850
22.1	18.8	14.9	245.0	8900	2.14	23.75	165	66	300	10700
26.5	22.5	17.9	290.0	10650	2.55	28.27	180	72	350	12700
31.1	26.4	21.0	345.5	12500	3.00	33.18	195	78	410	15000
36.1	30.6	24.3	400.0	14500	3.46	38.47	210	84	480	17400

* Actual blowing rate specified at 155 m³/min for each m² of cupola cross-sectional area in the melting zone (375 ft³/min for each ft²) to take into account satisfactory cupola operation at values within ±20% of this figure.

Air volumes refer to measurement at 15°C, 1,315 kPa.

† Recommended blower-volume capacity based on recommended blowing rate in Column 2 plus 20%; discharge pressure approximately 50% higher than anticipated windbelt pressure.

Tuyère shape has little influence on furnace behaviour.

It is possible to prevent slag solidifying round the inner end of the tuyères by locating an efficient valve or shutter in the down-comer pipe and using this to cut off the air supply. Closing the tuyères in rotation will keep the coke bed clear of serious obstructions, thereby ensuring both a consistent throughput and a melt with a uniform chemical composition and temperature.

The tuyères in modern, long-campaign cupolas project into the melting zone and are therefore water-cooled.

3.4 Diameter of Melting Zone

Blast rate controls both metal output and metal temperature at any specified coke charge rate. However, it is impossible to achieve the optimum blast rate if the furnace specified is too large or too small. Table 1 gives a guide to the internal diameters and melting zone areas required for a range of metal:coke ratios. The melting zone area can be calculated from the blowing rate, based on a specific blast rate of 115 m³/minute per m² of melting zone area. Once this is known, the internal diameter of the furnace can be calculated.

A common error, when an increase in melting rate is required, is to increase the cupola diameter to accommodate more iron in the stack. Unless the blast rate is increased in proportion, the result is cold iron. It is important to remember that furnaces operate satisfactorily within $\pm 20\%$ of the optimum blast rate, and an increase in melting rate can often be achieved by reducing the metal:coke ratio.

3.5 External Shell Diameter

When the internal diameter of a cupola has been decided, the external shell diameter can be derived from the required lining thickness. Generally, a thickness of 22.5 cm is satisfactory for a melting period of up to four hours. For a longer period (up to about eight hours) the lining thicknesses should be at least 30 cm to improve thermal efficiency and avoid lining distortion.

3.6 Shaft Height

The function of the shaft – that portion of the cupola extending from the tuyères to the lower edge of the charging door – is to accommodate a sufficient volume of metal and coke to absorb most of the heat from the ascending gases.

Table 2 summarises the requisite shaft height for cupolas at various melting rates if charge pre-heating is to be optimised. A shorter shaft height may be considered if gas combustion is required at the charging door: the shorter the shaft, the hotter the gas at the top of the shaft and the greater the ease of combustion – either spontaneous or assisted by an after-burner.

Table 2 Requisite shaft heights for cupolas

Melting rate of cupola	Height from tuyères to charging door sill		
	tonnes/hour	metres	feet
Up to 5		4.9	16
5 - 8		5.8	19
More than 8		6.7	22

3.7 Well Depth

The well collects the metal and slag melted in the upper part of the cupola and, because of their immiscibility and different densities, allows them to separate. The depth of the well, i.e. the distance from the tuyères to the tap hole, affects the chemical composition of the iron produced. This applies to both intermittently tapped and continuously tapped cupolas. Well depth also has an important influence on carbon pick-up and on the tapping temperature of the metal.

If the well depth is increased to achieve additional carbon pick-up, some temperature loss must be accepted. It may be possible to compensate for this loss by using either oxygen injection or enrichment in the combustion air (or by using an electrically heated holding furnace, if available).

3.7.1 Intermittently Tapped Cupolas

The well depth in an intermittently tapped cupola should be sufficient to:

- ensure good mixing of the molten iron;
- allow production of the largest casting from a single tap;
- hold all the slag produced between deslagging operations.

Typically, deslagging is carried out every hour, and requires an increase in well depth by 38 cm (15 in) to accommodate the build-up of slag.

Fig 3 shows the relationship between cupola/well diameter and well capacity. It assumes that half of the well volume is occupied by coke.

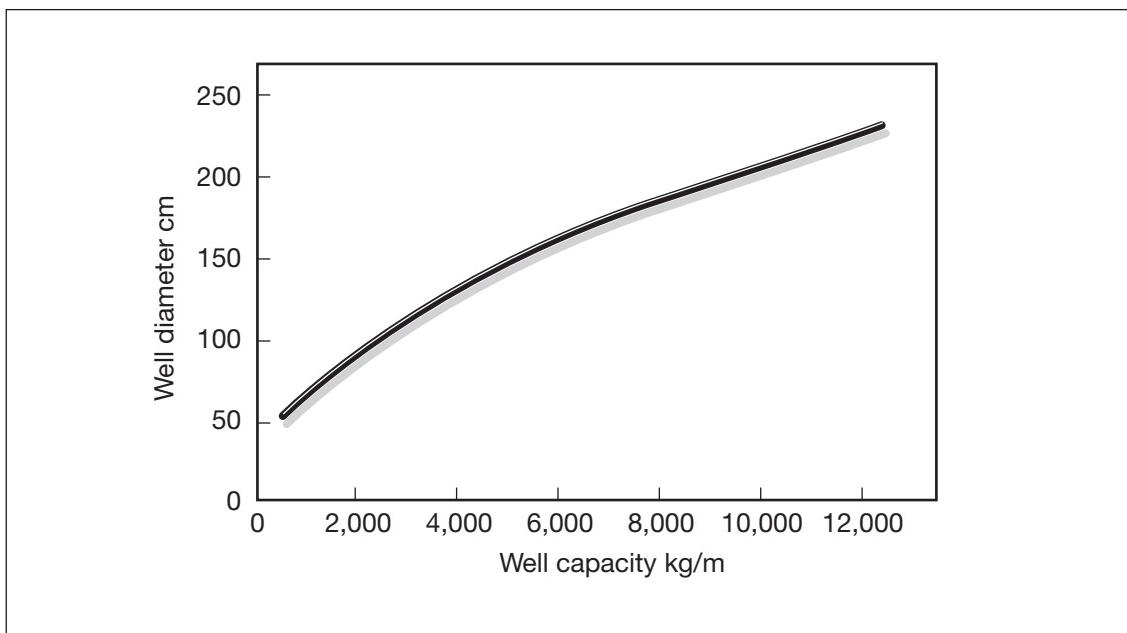


Fig 3 Influence of cupola diameter on well capacity

It is important to remember that no heat is generated in the well, but that heat is lost through the well lining. Too deep a well, therefore, increases the temperature loss of the metal held and, in addition, may impede the complete and uniform ignition of the coke bed below the tuyères. This will result in cold metal during the early part of the melt.

Restricting the metal charge weight to one-tenth of the maximum hourly output or less should ensure adequate mixing of the molten iron without requiring an undue increase in well depth.

3.7.2 Continuously Tapped Cupolas

In continuously tapped cupolas, very little metal is held in the well, and mixing capacity is normally provided by a receiver or collecting ladle. Nevertheless, the depth of the well should be sufficient to prevent slag entering the tuyères at the lowest anticipated blast rate.

3.8 Cupola Linings

3.8.1 Lining Materials

The lining of a cupola must be thick enough to withstand the wear and tear of daily operation. It may be made of firebrick or of rammed or gunned refractory material.

Firebrick linings should consist of two concentric rings of circle bricks, or blocks of appropriate thickness. The radius in each case should be correct for the internal diameter required. Bricking rings, which generally take the form of angle-iron shelves, should be provided to support the lining. The first of these should be placed approximately 1.5 m (5 ft) above the tuyères, with others at 1.5 – 2.0 m intervals.

The outer ring of a firebrick lining will normally last for a considerable period, with only the inner ring requiring regular replacement. Minimising the thickness of the joints between bricks will help to limit the slag attack that results in poor lining life.

It is often desirable to restrict the thickness of a rammed or gunned lining to about 10 cm and to surround this with an outer ring of firebricks. A greater thickness of rammed material is difficult to dry and fire.

The use of hollow cast iron blocks in the upper part of the shaft helps to minimise the impact of the materials charged.

Above the charge door, the stack can be lined with a single layer of firebrick circle or key bricks.

Starting a campaign in a newly bricked cupola requires extra care. It is important to limit thermal shock to the lining by not overblowing the furnace. Many linings are significantly eroded when newly bricked cupolas are blown excessively.

3.8.2 Water Cooling

When foundry practice requires cupola operation for longer periods than a single shift of about six hours, water cooling can eliminate the need for a very thick lining. Water cooling is applied to the external surface of the cupola shell from just below the tuyères to a level 1.5 m or more above them. The water is provided from a spray ring and is collected in a trough below the tuyères. A slightly tapered shell that widens towards the base helps to maintain a continuous water curtain over the shell.

External water cooling is also used:

- as a precautionary measure in case the lining should burn back to the shell at the plane of maximum burn-out: maintaining a substantial refractory thickness avoids the high heat loss associated with a completely liningless, water-cooled melting zone;
- to allow a reduction in lining thickness, thereby opening up the internal diameter of the cupola and permitting an increase in output.

Water cooling requires the windbelt to be detached from the shell.

The water used for cooling should be pH controlled and include a corrosion inhibitor.

3.8.3 Liningless Operation

In liningless operation, a considerable amount of the heat generated within the cupola is lost through the shell to the cooling water. The proportion transmitted to the cooling water in this way is inversely proportional to the cupola diameter and increases with the height of the water-cooled zone (Fig 4).

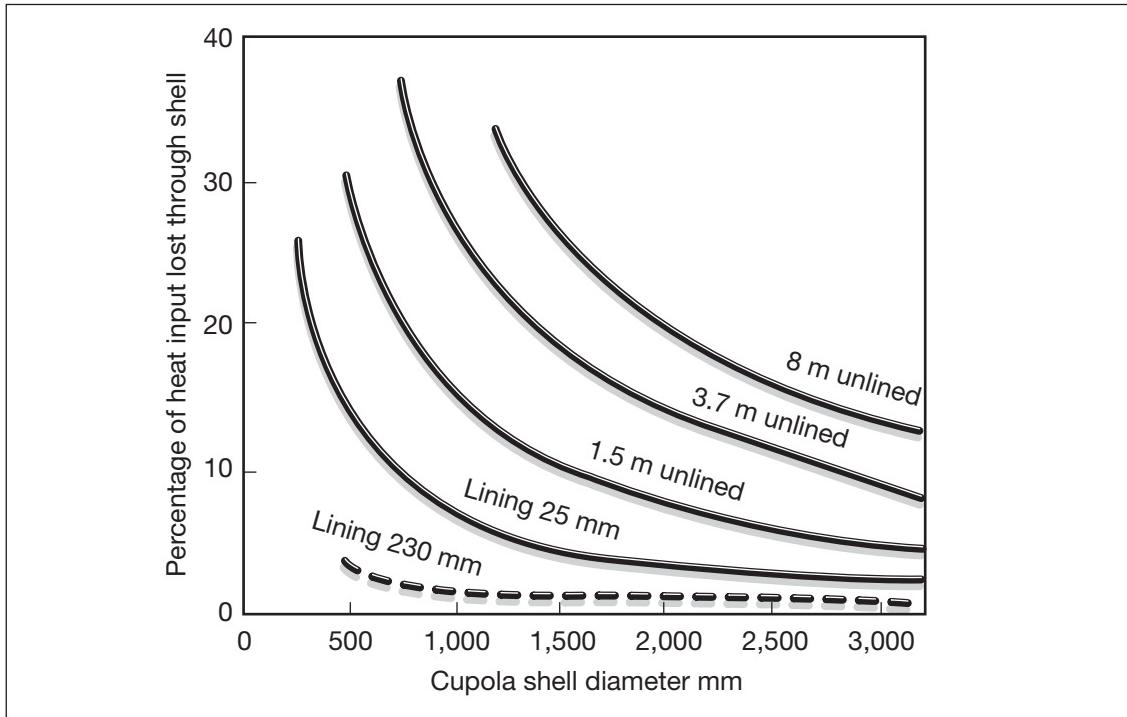


Fig 4 Heat losses through the cupola shell

Liningless operation is not recommended for cupolas with an internal diameter of less than 1.5 m. It should rather be applied to cupolas of relatively large capacity, where melting campaigns are long and operation is for more than 16 hours/day.

Using liningless water-cooled cupolas for long-campaign operation offers several advantages:

- only one cupola is required;
- the daily consumption of bed-coke is reduced;
- campaign monitoring is facilitated by the constant diameter of the cupola and more consistent melting conditions.

It is advantageous to apply a thin refractory coating, 30 – 50 mm thick, to the internal surface of the water-cooled section, although it is difficult to retain this coating in full over an extended melting period. However, internal cupola repairs can be carried out on a regular basis – after one or perhaps several weeks of operation.

To offset the water cooling losses, liningless cupolas often use a hot blast and are fitted with water-cooled projecting tuyères (Fig 5). The advantages of this type of system are described in Energy Efficiency Best Practice Programme Good Practice Case Study 366: *Long Campaign Hot Blast Cupolas in Iron Foundries*¹.

¹ Free copies of this Case Study can be obtained from ETSU.

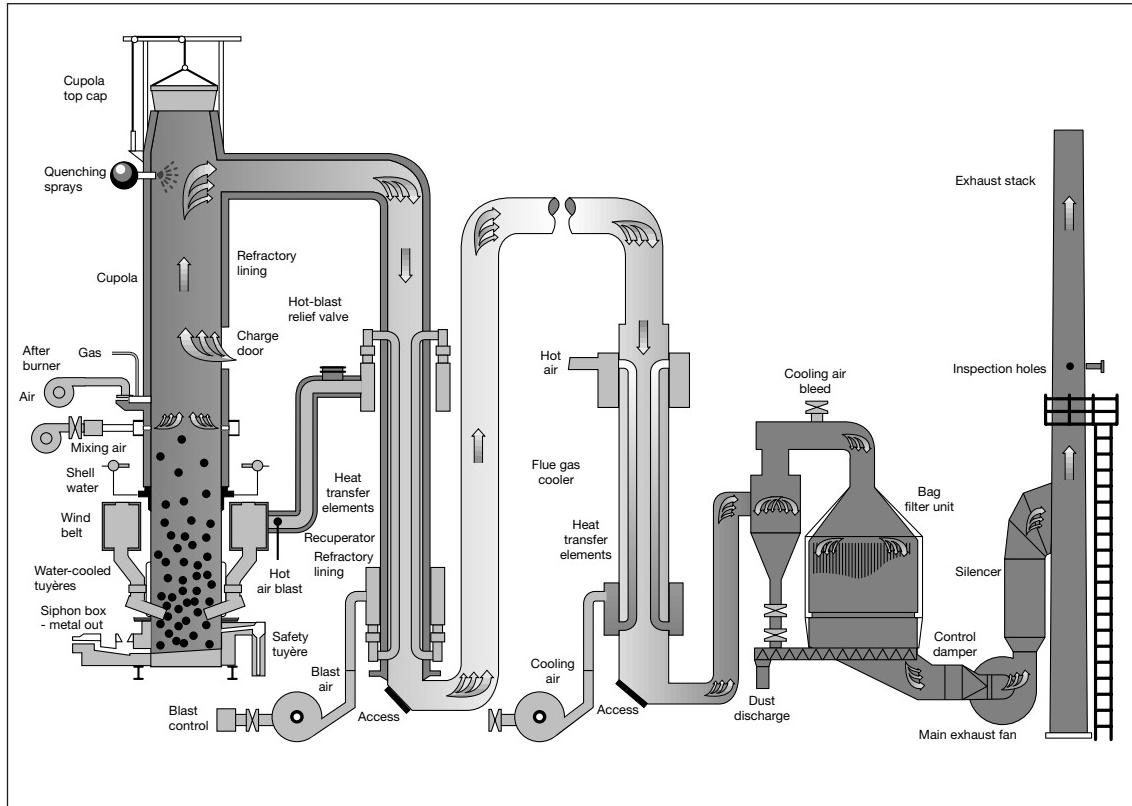


Fig 5 Schematic of hot blast cupola

3.9 Divided Blast Cupola Operation

A first step towards reducing the melting costs of conventional cold blast cupola operations is either to install a furnace with, or convert an existing furnace to, divided blast operation. Divided blast operation is a cost-effective method of improving the economics for a modest investment, and significant savings can be achieved.

The cupola is equipped with two rows of tuyères, each of which is supplied with a measured and controlled quantity of blast air via a separate windbelt and a separate blast main (Fig 6). The two rows should be about 1 m apart, irrespective of cupola diameter.

The advantages of using a cupola with the blast divided equally between two rows of correctly spaced tuyères vary with the approach. If the charge-coke consumption is maintained at the level used in an equivalent conventional cupola fitted with a single row of tuyères, there are three main advantages:

- a 45 – 50°C increase in the metal-tapping temperature;
- an increase in carbon pick-up of approximately 0.06%;
- an increase in the melting loss of silicon of approximately 0.18%.

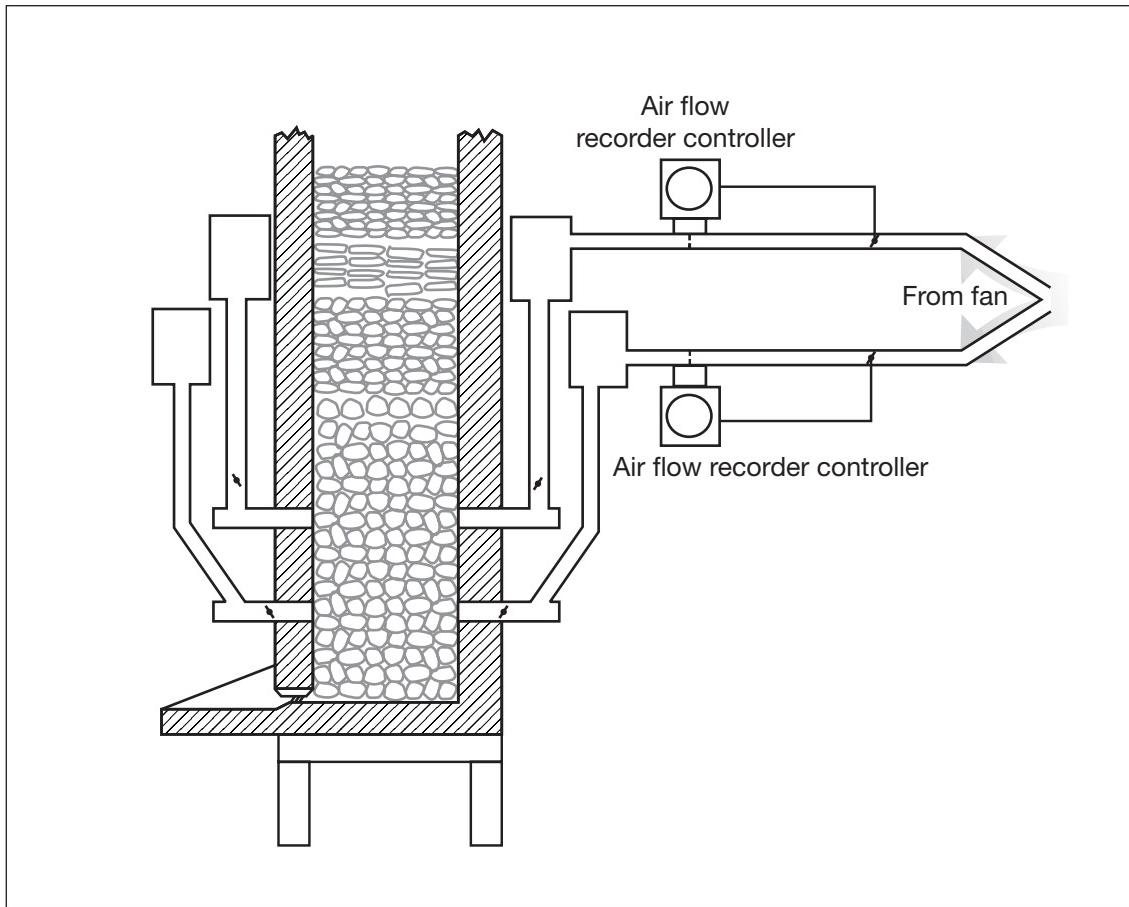


Fig 6 Schematic of divided blast cupola

If the metal-tapping temperature is maintained at the level achieved in an equivalent conventional cupola, the advantages include:

- a reduction in charge-coke consumption of 20 – 32%;
- an increase, if required, of 11 – 23% in the melting rate.

Because these benefits are only maximised when the blast is split equally between the top and bottom rows of tuyères, it is important to measure and control the air-flow in each blast main. This requires two air-flow metering instruments and separate control valves. The control valves can be operated manually, but it is preferable to install automatic air-flow control equipment that can be pre-set to maintain a desired blast rate.

It is strongly recommended that the blast for both mains should be supplied from a single fan.

NB: If separate fans are used, the fan motor starters must be interconnected so that one fan cannot operate without the other. This prevents air being blown to only one row of tuyères. It also prevents cupola gases entering the second row of tuyères, windbelt and blast main, which would cause an explosion.

The design should incorporate normal safety features to guard against possible explosions during bed light-up and blast-off periods. Such features include explosion doors or discs, check-valves or relief valves, tuyère sight-hole flaps and elbow valves. In addition, the cupola isolating valves on the mains supplying the upper and lower windbelts should be linked so that they operate together.

Before the start of a melt it is necessary to measure and adjust the coke bed to a pre-determined level above the top row of tuyères. Since the upper row of tuyères is generally 1 m above the lower row, the total coke-bed height above the tap-hole will need to be increased by a similar amount when a cupola is converted to divided blast operation.

Where melts are of short duration, i.e. less than about 2 – 3 hours, the saving in charge coke does not usually compensate for the additional bed-coke requirement. Nevertheless, even on short melts, the higher tapping temperature and carbon pick-up that can be achieved with divided blast operation can be advantageous to many foundries. However, the lining burn-out pattern extends further up the furnace shaft.

3.10 Oxygen Use in Cold Blast Cupola Operation

The use of oxygen in a cupola provides a higher combustion temperature, improving heat transfer and, because the blast air subsequently contains less nitrogen, ensuring that more heat is available for transfer to the metal. Typically, 1 – 3% additional oxygen is used in cold blast cupolas.

Compared with normal operation, the *continuous use* of oxygen in a cold blast cupola can give rise to a number of improvements:

- If the charge-coke consumption is held at the level used prior to oxygen enrichment, the net result is a higher metal temperature, increased carbon pick-up and a lower melting loss of silicon.
- If the metal temperature is maintained at the pre-oxygen enrichment level, coke consumption will fall. However, this also means that there will be no increase in carbon pick-up nor any reduction in the melting loss of silicon.
- The output from an existing cupola can be increased well beyond its usual optimum melting capacity because of the higher melting rate. If no increase in temperature is required, and the coke charge is reduced, an even greater increase in melting rate can be achieved with the same blast rate and level of oxygen enrichment.
- It is also possible to replace some of the pig iron with cast iron or steel scrap while still achieving higher metal temperatures and carbon pick-up. This gives rise to metal cost savings.

The *intermittent use* of oxygen in a cold blast cupola can also be effective, offering two main benefits:

- Where oxygen is used to achieve the required temperature very rapidly, either at the start of a melt or following shut-down, there are savings in pigged metal and also a reduced incidence of casting defects associated with the use of cold metal.
- It is possible to achieve a higher rate of output over short periods.

However, using oxygen incurs ongoing costs. The oxygen has to be distilled from air and then transported to the foundry. Both processes incur some energy cost. The foundry also has to purchase the oxygen, so the impact of its use on melting costs will depend on the price at which it can be purchased as well as on the amount used. While foundries with a larger demand for oxygen can generally buy it more cheaply than those with a limited requirement, the economic case for oxygen use has still to be established at the individual foundry level.

Ongoing costs of this type are not encountered with conversion to divided blast operation once the one-off capital outlay has been paid. The normal approach would, therefore, be to convert to divided blast operation before considering oxygen use.

The effectiveness of oxygen enrichment depends on the way in which it is introduced into the cupola. Three processes have been developed (Fig 7).

- **Direct enrichment of the blast supply.** Typically, around 3% oxygen is fed into the blast main, where it mixes with the combustion air before entering the cupola through the tuyères.
- **Injection into the well.** Oxygen is fed via a ring-main to water-cooled injectors, the number of injectors varying with cupola size. The oxygen is injected into the coke-bed beneath the tuyères. This method of oxygen enrichment is at least twice as effective as direct enrichment of the blast supply. However, it is usually confined to continuously tapped cupolas because, with intermittent tapping, there is a risk that slag and/or metal may rise to the level of the injectors.
- **Injection at the tuyères.** Oxygen is introduced into the cupola through injectors inserted either into each tuyère or into alternate tuyères. The effectiveness of this method lies somewhere between direct blast enrichment and well injection.

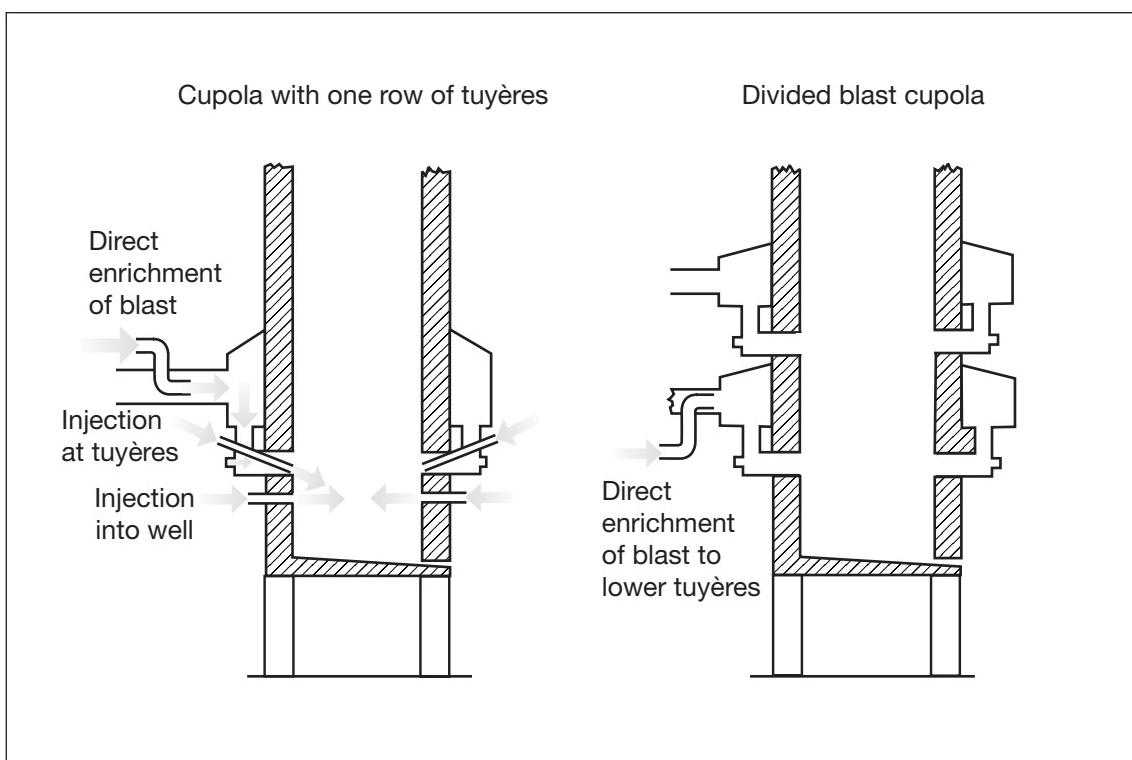


Fig 7 Oxygen enrichment and injection

When oxygen injection is compared with a conventional cold blast cupola with one row of tuyères, the approximate increases in tapping temperature obtained for a given consumption of charge coke are as follows:

- blast enrichment +15°C;
- well injection +85°C;
- tuyère injection +40°C.

Where oxygen injection is compared with divided blast operation, the increases are much smaller. As indicated in Section 3.9, conversion from conventional to divided blast operation can increase the tapping temperature by 50°C. Using oxygen to enrich the blast supply to the lower row of tuyères of a divided blast cupola gives a further increase in tapping temperature of 35°C – a total of 85°C. No greater benefits can be achieved in divided blast operation using either well or tuyère injection.

3.11 Hot Blast Operation

Hot blast operation involves pre-heating the cupola blast air before it is injected into the cupola. This speeds up the reaction between oxygen and the charge coke, and reduces the chilling effect of the incoming air. Compared with conventional cold blast cupolas, hot blast operation reduces the amount of charge coke required to produce iron at a given temperature by about 30%. More importantly, if the quantity of charge coke is maintained at the level used for cold blast operation, there will be an increase in carbon pick-up, allowing the replacement of pig iron with steel scrap in the furnace charge.

There are two main options for pre-heating the blast air in a heat exchanger:

- recuperative systems, which extract heat from the cupola waste gases;
- independently fired oil or gas heaters.

Recuperator systems are recommended because their operation increases both energy and thermal efficiency (Fig 8). Furthermore, all cupola waste gases must now be burnt to remove their carbon monoxide (CO) content before they are discharged to atmosphere. Burning these gases in the combustion chamber of a recuperator allows the recovery of useful reaction heat. Burning the same gases in the flare stack of an independently fired system recovers no useful heat.

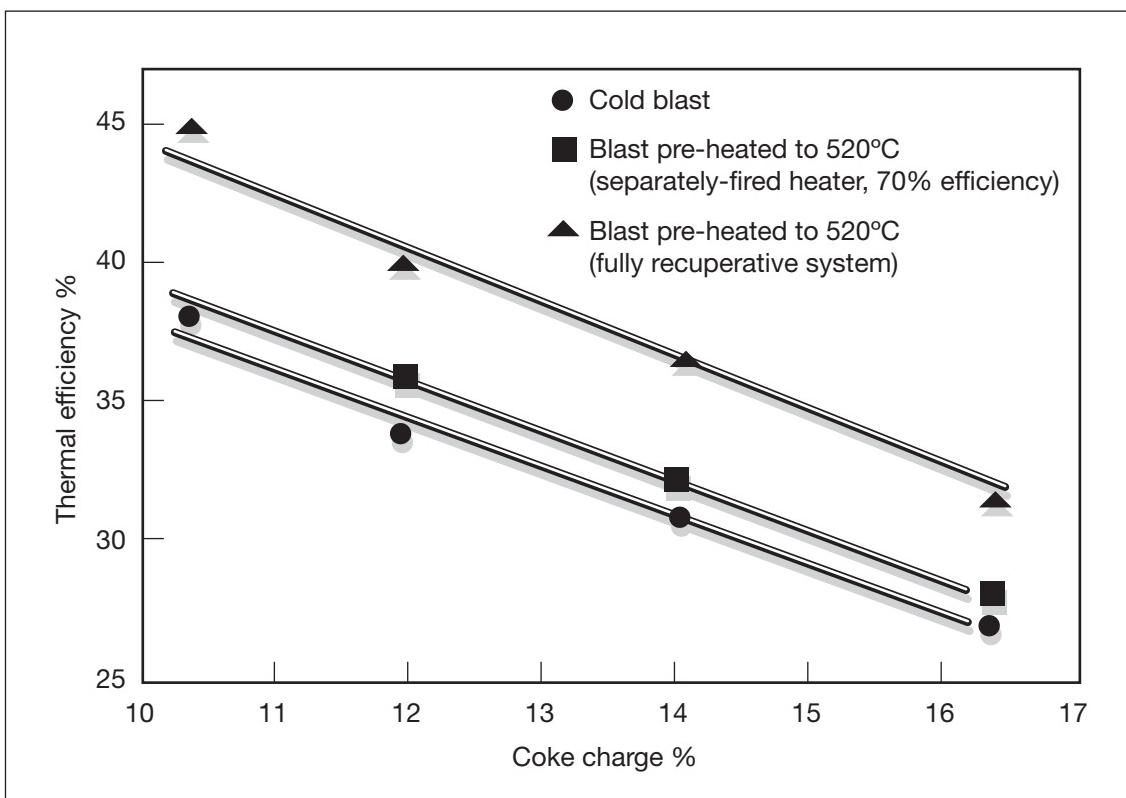


Fig 8 Effect of blast pre-heating on furnace efficiency

The temperature of the hot blast is generally restricted to 500 – 600°C. Heat exchangers designed to provide blast temperatures in excess of 600°C must be manufactured from more expensive, very heat resistant materials, and this increases the cost of recuperation.

Fig 5 shows a typical hot blast cupola that is fitted with four, protruding, copper spiral-sheathed tuyères which are water-cooled. Combustion of the off-take gases is maintained by the combination of an annular air-mixing ring located below the charge door and an after-burner which automatically ignites if the temperature of the rising gases falls below a pre-set level. The off-take gases are drawn from the cupola through a recuperator, and heat is transferred to the incoming blast air, which reaches a temperature of 490 – 500°C. The hot blast air is enriched with 1.5 – 2.0% oxygen. The waste gases are then cooled to approximately 175°C. They pass through a dry bag filter unit before being discharged to atmosphere via a 25 m high stack.

Although hot blast operation involves considerable capital investment, substantial energy savings are achievable as a result of reduced coke consumption, and lower maintenance and relining costs. Savings of £17.40 per tonne of good castings have been claimed. In addition, the plant is more environmentally effective with particulate emissions generally below 5 mg/m³.

Hot blast operation offers several advantages:

- reduced coke consumption;
- increased metal temperature;
- a higher melting rate;
- reduced sulphur pick-up;
- lower melting losses;
- increased carbon pick-up.

Not all of these benefits are attainable simultaneously.

While the hot blast cupola will always be better suited to volume metal production, advances in technology are extending its economic range down to minimum melting rates of 6 tonnes/hour. This compares with the 10 tonnes/hour commonly accepted as the ‘minimum’ size in the UK a few years ago, when emissions legislation was more stringent for hot blast units than for cold blast operations.

Further information on hot blast cupolas can be obtained from Good Practice Case Study 366: *Long Campaign Hot Blast Cupolas in Iron Foundries*.

3.12 Continuous Tapping Systems

A foundry’s decision on whether to use an intermittent or a continuous tapping system ultimately depends on specific conditions at the foundry concerned. Continuous tapping does, however, offer certain advantages and disadvantages.

Advantages

- A constant, albeit relatively small, quantity of metal is maintained in the well.
- The metal has a brief but uniform period of contact with the coke, which minimises the variation in carbon pick-up.
- Using continuous tapping in conjunction with a receiver of sufficient holding capacity allows melting to be controlled at a steady rate, even when metal demand is variable. This ensures uniformity of metal temperature and composition.
- Continuous tapping eliminates many operational difficulties, e.g. hard and leaking tapholes, and slag in the tuyères and ladle.

Disadvantages

- The quantity of metal stored in the cupola well is limited, and a receiver that can hold sufficient metal to even out fluctuations in composition is, therefore, usually required.
- Although the metal temperature at the taphole may be higher than that achieved with intermittent tapping, the metal flow rate is low and there is a substantial temperature drop as the metal runs down the launder and accumulates in the receiver or ladle.

3.12.1 Continuous Front Tapping and Slagging

Continuous front tapping involves collecting both metal and slag in a refractory-lined box attached to the outside of the cupola at the taphole. The slag is generally separated from the metal by a dam and is collected continuously (Fig 9). Slag-free metal then passes to a launder, for collection and distribution to the foundry.

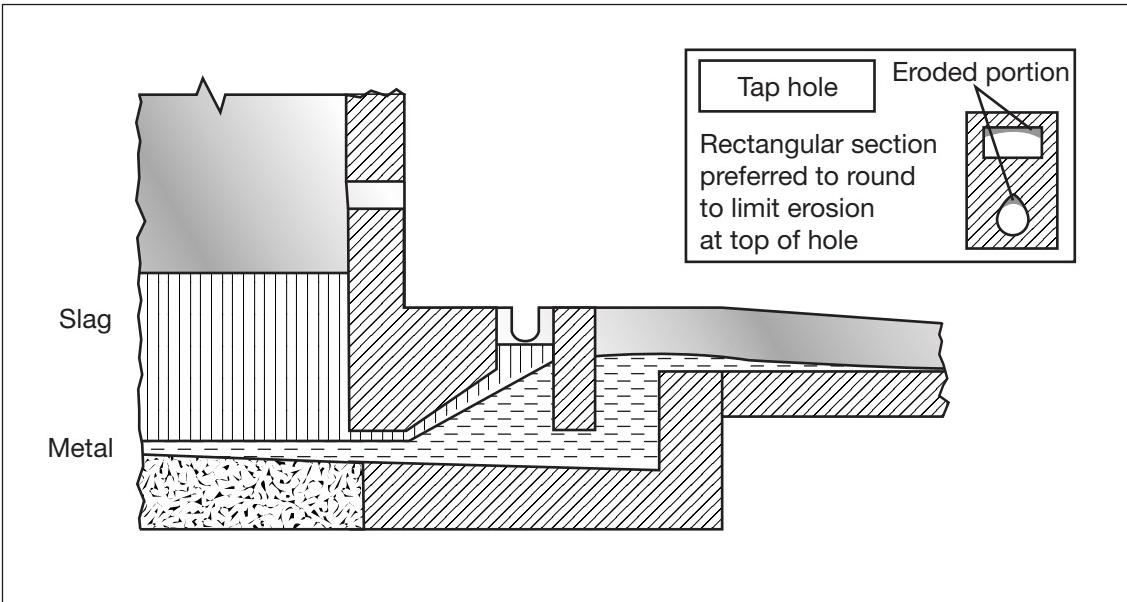


Fig 9 Continuous front tapping and slagging

3.12.2 Continuous Front Tapping and Rear/Side Slagging

Continuous front tapping and rear/side slagging (Fig 10) involves withdrawing the metal and slag through separate siphons. The slag hole is not opened until melting has been under way for between half an hour and an hour. This ensures that a sufficient quantity of slag has accumulated in the well to flush and heat up the system and to avoid freezing up. Careful observation during this period will ensure that the slag does not reach the level of the tuyères. Provision must also be made to drain the well at the end of the melting shift.

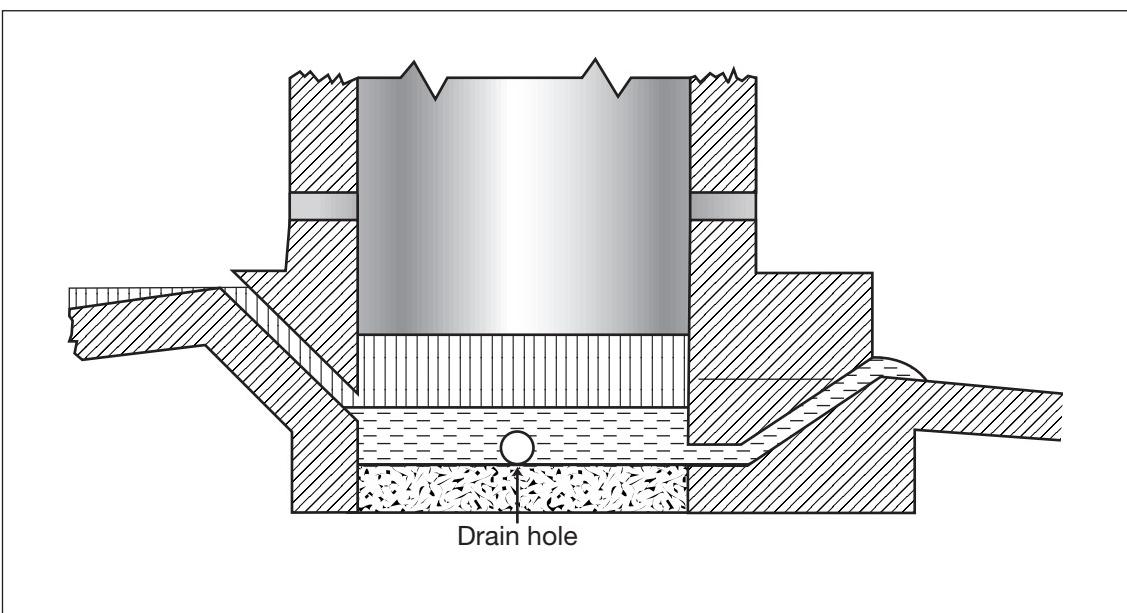


Fig 10 Continuous front tapping and rear slagging

Although this approach is generally restricted to larger cupolas, it does have certain advantages over continuous front tapping and slagging:

- The amount of metal held in the cupola well can be controlled by designing the metal and slag siphons appropriately.
- The refractory materials selected for the metal and slag holes and containers can be varied to suit the requirements of the product. For example, the slag hole and siphon box can be constructed of carbon ramming paste, while the metal hole and box is more appropriately constructed of graphite, ganister or plastic high alumina ramming material.

3.12.3 Siphon Brick Tapping System

The siphon brick tapping system is most often applied where small quantities of metal are required at regular intervals, for example in hand shanks. Metal passes from the cupola through an opening at the back of the siphon brick (Fig 11) into a channel and thence up through the centre of the brick. On the front of the brick there are several tapholes, each connected to the central channel. On the right side of the diagram, a ladle is shown receiving the metal.

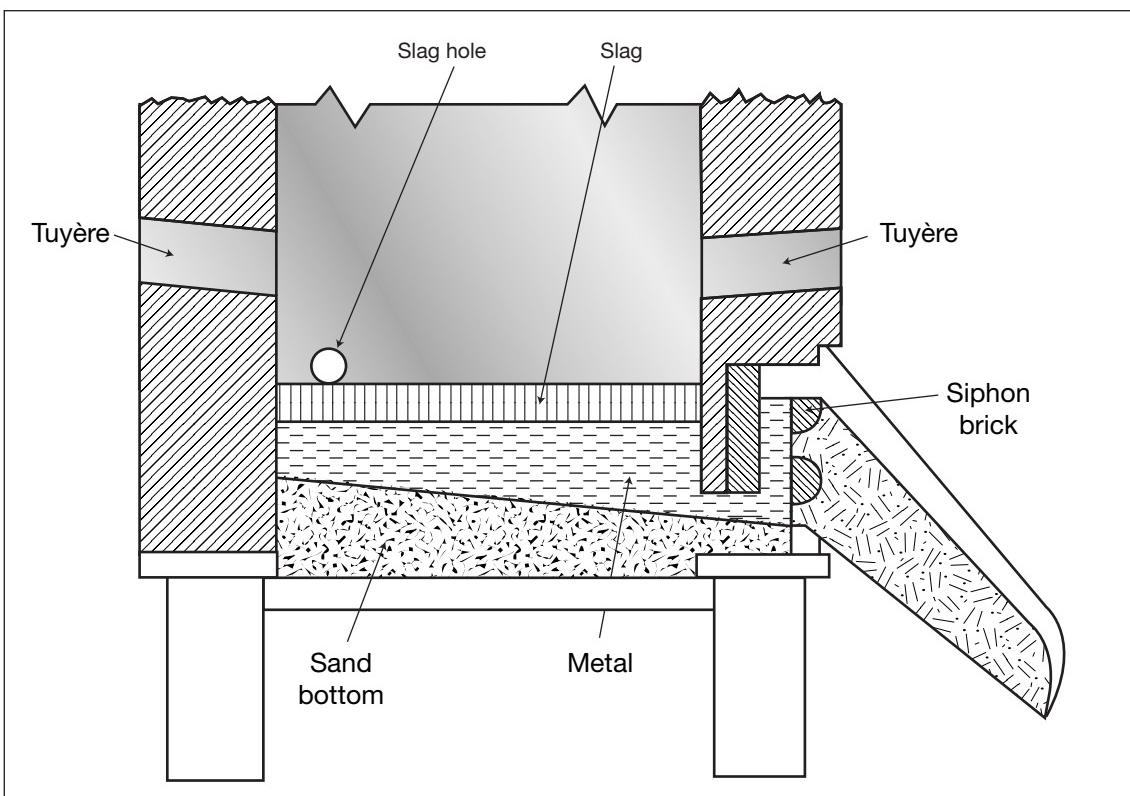


Fig 11 Siphon brick tapping

At the beginning of the melt, all the tapholes are left open. As metal starts to melt it is allowed to run through the bottom hole until it is thoroughly heated. This hole is then closed with a plug or with sand and the metal is permitted to rise up the central channel and flow out through the second hole. The procedure is repeated until metal flows from the highest taphole.

To stop the flow from the taphole, the blast is reduced or shut off. This reduces the internal pressure in the cupola well, causing the metal level in the well to rise and the metal level in the siphon brick to fall.

Thereafter, metal is tapped by opening the blast valve to increase the pressure and cause metal to flow out through the taphole, and then partially or completely closing the valve once the ladle has been filled.

Slag may be removed either intermittently or continuously via a slag hole located at a convenient distance below the tuyères. If slag is allowed to collect, the amount of metal held in the well will be correspondingly less, and there is some justification for keeping the slag hole open continuously to optimise mixing of the charge components.

Operating a cupola in this way with intermittent blowing means that more coke is required to maintain the metal temperature than with conventional operation. Furthermore, as melting is very slow when the blast is off, this type of operation will not give the metal output that can be obtained with continuous blast on a furnace of the same internal diameter. Therefore, when a cupola is to be operated using siphon bricks, its rated output should be considerably in excess of that actually required.

It is also possible to use the siphon brick to obtain an uninterrupted supply of metal from the cupola. In this case, the blast is maintained and metal flows from the taphole at the rate at which it is melted. This mode of operation requires either a tilting spout or a receiver. On very long shutdowns it may be necessary to drain off the slag and then drain the well by opening the bottom taphole of the siphon brick. The well must be drained in this way at the end of the melt before the bottom is dropped.

3.13 Slag Handling and Uses

The growing costs of disposal, combined with waste-related legislation and landfill taxes, have meant that more and more effort is being put into finding beneficial uses for ‘waste’ materials.

Slag is a foundry by-product that, because of its particular glass-like properties, cannot easily be handled or used for any form of waste heat recovery. Furthermore, it is not advisable to allow slag that has been tapped from the cupola to fall on to the foundry floor because it:

- creates a hot and dangerous working environment around the furnace;
- is a hazard to foundrymen;
- restricts access to the cupola;
- increases labour costs, as cooled slag must be broken up and loaded before disposal.

Collecting slag in sand-lined cast iron or fabricated steel containers or using slag granulation techniques promotes safe and acceptable working conditions in the cupola area and reduces the labour costs for slag collection and removal. Adequate slag disposal is particularly important for cupolas operating for eight hours or longer.

The choice of slag collection/disposal method depends on:

- the quantity of slag being produced;
- the cost of handling the containers;
- the practicality of installing slag granulation equipment within the existing foundry layout.

It is usually difficult to justify slag granulation where cupolas operate only short melting campaigns, ie campaigns of less than eight hours. If the foundry can identify an outlet for the recovered slag that will allow its beneficial re-use, it will recover its investment in the energy needed for granulation.

Water-quenched slags can now be used as a substitute for coarse aggregate in the manufacture of blocks for the construction industry and also as an abrasive in various shotblasting processes. There is some potential for using slag as a liming agent for soil treatment.

In the case of air-cooled cupola slags, there are several possibilities for re-use:

- coarse aggregate substitute;
- road base construction;
- ballast;
- brickmaking;
- decorative ground cover;
- asphalt;
- insulating wool.

The following publications offer further information on this subject:

Environmental Technology Best Practice Programme

GS 25	<i>Saving Money Through Waste Minimisation: Getting Started</i>
GG 25	<i>Saving Money Through Waste Minimisation: Raw Material Use</i>
GG 27	<i>Saving Money Through Waste Minimisation: Teams and Champions</i>
ET 30	<i>Finding Hidden Profit - 200 Tips to Reduce Waste</i>

Energy Efficiency Best Practice Programme

NPCS 111	<i>Slag-bound Material in Road-base Construction</i>
NPR 111	<i>Slag-bound Material in Road-base Construction</i>

All these publications can be obtained free of charge from ETSU.

The Castings Development Centre has also, under the Department of Trade and Industry's Sector Challenge Initiative, prepared a publication entitled *Beneficial Re-use for Managers*. This can be obtained free of charge from the Castings Development Centre².

Checklist for Energy Efficient Design

- Optimise cupola design parameters in accordance with recommendations.
- Ensure that the air blower is of sufficient capacity.
- Consider divided blast operation.
- Use oxygen enrichment of the air blast.
- If replacing melting plant, examine the advantages of hot blast operation.
- Examine prospects for the beneficial re-use of waste materials.

² Castings Development Centre, Alvechurch, Birmingham, B48 7QB. Tel: 01527 66414. Fax: 01527 585070.

4. OPERATIONAL CONTROL

4.1 Overview

Furnace efficiency is optimised by measuring and controlling the blast rate. It is possible to reduce coke consumption and improve cupola performance by continuous blowing and by avoiding stop/start situations.

The success of a cupola melt is determined largely by the effectiveness of coke bed preparation, ignition and consolidation procedures prior to addition of the metal charge. Raw material selection is also important, i.e. the size and cleanliness of the metallics and the quality of the coke used. All materials charged must be accurately weighed.

Careful consideration should be given to the adequacy of the metal handling and distribution system which, if unsatisfactory, can easily outweigh the benefits of efficient melting.

4.2 Blast Rate Measurement and Control

A cupola will only perform satisfactorily if it is operated correctly, with careful control of factors such as blast rate and the ratio of coke to metal. Incorrect operation will adversely affect efficiency, melting costs and energy consumption and costs.

Effective blast rate control is particularly important as it helps to ensure consistent and replicable melting conditions. Control equipment that automatically regulates either the volume or weight of air delivered to a cupola is commercially available (Fig 12). Air volume control is achieved by setting the measuring instrument to the required blowing rate. The control mechanism then delivers a pneumatic impulse to actuate a valve either in the blast main (centrifugally blown system) or in the bleed-off duct (positive displacement blower system).

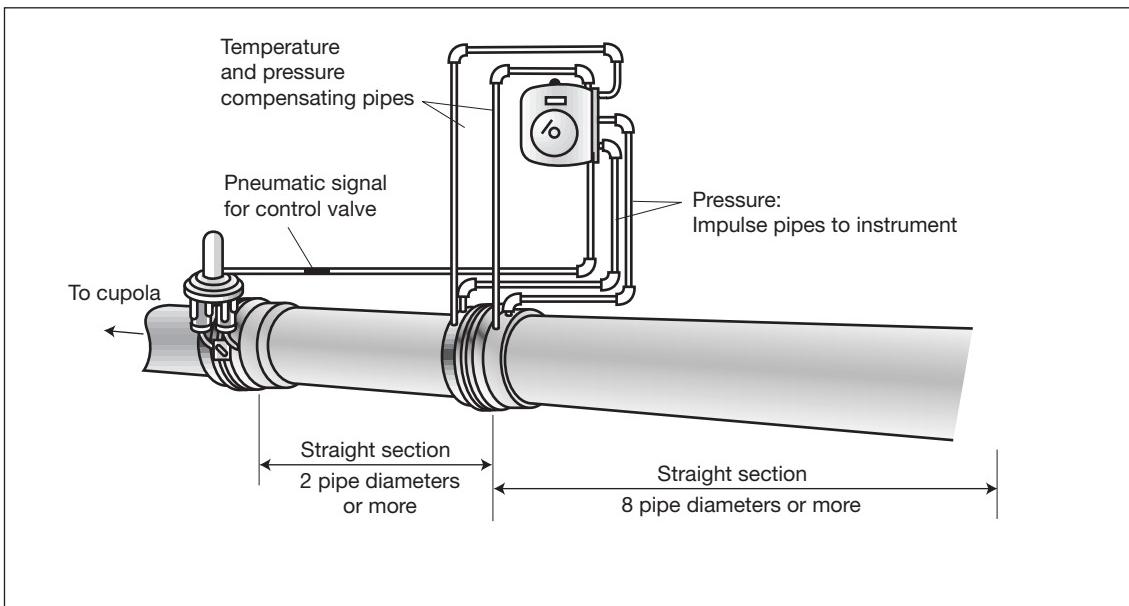


Fig 12 Air weight control system

Many cupolas are provided with a gauge which measures the air pressure in the windbelt. The blast supply is then regulated according to the readings obtained. However, the relationship between blast pressure and blast rate varies widely both between cupolas and also during the operation of any particular cupola. For example, if the tuyères slag over very badly, the blast pressure will increase but the air flow through the cupola will actually fall because of the restriction. Furthermore, the increased blast pressure will suggest that the blast rate has actually increased, causing the blast control valve to close in an attempt to regulate the rate.

Other factors can also affect windbelt pressure and give a false indication of blast rate. Examples include the nature of the charge, the size of the coke and the level of stock in the shaft.

It is clear from this that the blast rate can only be controlled satisfactorily using an air flow meter. This is particularly the case where cupolas are operated continuously for long periods and/or where it is important to ensure close control of melting rate, metal temperature and metal composition.

Although a correct combustion air supply is essential for efficient cupola operation, the air supply is often adversely affected by:

- air losses from the wind main, tuyère boxes and windbelt because of inadequate maintenance;
- temporary patches that have been introduced to reduce serious air losses;
- slag holes on intermittently tapped cupolas that are oversized or have been left open, resulting in the loss of, typically, up to 20% of the delivered air.

A cupola that is blown intermittently will also be inefficient in operation, resulting in a reduced metal temperature (Fig 13). Shutting off the blast frequently to match an intermittent demand for metal is likely to:

- reduce average tapping and pouring temperatures, with the consequent risk of defective castings;
- increase the variation in metal composition, particularly the carbon and silicon contents;
- increase coke consumption as the operator attempts to improve tapping temperature;
- affect the degree of nucleation of the iron and increases its shrinking tendencies.

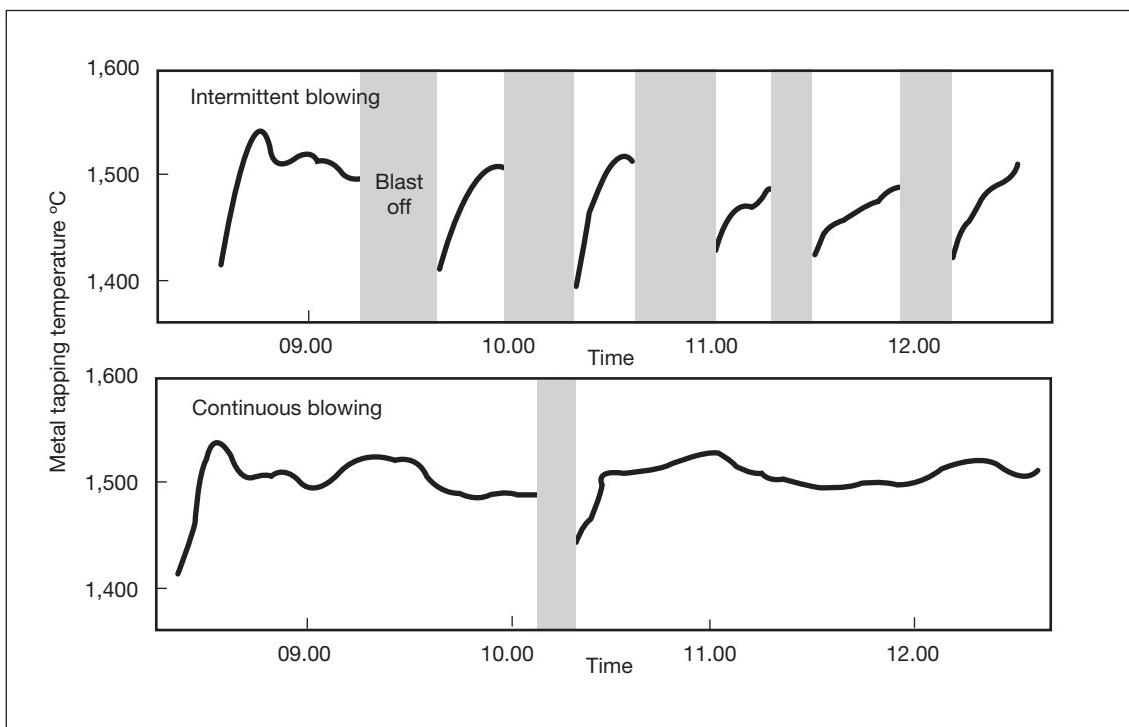


Fig 13 Influence of intermittent blowing on metal temperature

Moulding and casting schedules should, therefore, be programmed to produce a reasonably constant demand for metal. This will minimise – or even eliminate – the need for blast shut-off periods or for significant variations in the blast rate.

Where large fluctuations in demand are unavoidable, foundries should consider installing an electric holding furnace. This will provide a large buffer reservoir of metal to take up variations in demand, allowing the cupola to be operated continuously at a reasonably consistent blast rate and evening out variations in temperature and composition. The economics of installing a holding furnace must be carefully considered, particularly in foundries where production rates are relatively low.

4.3 Charge Materials

4.3.1 *Metallics*

The quality and nature of the metallic materials charged into a cupola can affect both furnace operation and the quality of the iron produced. Producing castings that have to be scrapped represents a significant waste of energy.

There are two main points to be considered in relation to charge materials:

- cleanliness;
- the size and weight of individual charge pieces.

Certain types of scrap can contaminate the iron, adversely affecting the quality of the castings produced. Furthermore, excessive amounts of dirt, oxide or other contaminant mean that fluxing is necessary, and this generates more slag, wasting energy and adding to the materials cost of the operation.

Oversized material may adversely affect the correct progression of a melt by causing ‘bridging’ or ‘scaffolding’ in the cupola shaft. Ideally, the length of the individual pieces of charge should be less than a third of the cupola shaft diameter. The use of excessively large and heavy pieces can also significantly reduce metal temperature, thereby increasing the risk of producing castings that have to be scrapped.

Table 3 lists the results of poor control over the selection and use of raw materials for metal production.

In order to calculate the proportion of the various types of metallic material that comprise the cupola charge, the foundry operator needs to know the compositional changes that will occur during melting. Carbon content will nearly always increase, but there are many factors that affect the amount of carbon pick-up, such as the initial carbon content of the charge, the silicon and phosphorus content of the iron, the amount of coke used in the charge, the core temperature of the bed, the depth of the cupola well, the method of tapping the metal and the final metal temperature. Many of these factors are interdependent. Slag composition is also an important factor in achieving the desired carbon content.

Oxidation of silicon and manganese always occurs during cupola melting. Average losses amount to 10 – 20% of the quantities charged, although losses do vary with melting technique. High tapping temperatures, for instance, reduce losses, while an increase in the proportion of steel scrap in the charge will normally increase the level of loss.

The sulphur content of the charge always increases as a result of acid cupola operation. The increase is dependent on many factors, especially the sulphur content of the coke and the slag basicity. In normal cold blast operation, sulphur pick-up is difficult to predict. However, a foundry using a good quality European metallurgical coke can expect an ‘as-tapped’ sulphur content in the 0.08 – 0.15% range.

Table 3 Effect of charge materials on casting quality

Raw material	Examples of lack of control	Immediate effect	Effect on casting quality
Pig iron	Required composition on purchase order Advice note information on chemical composition not used Batches not segregated and identified in the stockyard No occasional checking of composition by the laboratory Batches not used in accordance with composition	Variable or incorrect metal composition	Metal not to specification Metal too hard with chill in free edges Metal too soft Shrinkage-porosity defects
Cast iron scrap	Return scrap not segregated by grade Bought scrap not segregated by grade	Charge composition not correct	Metal not to specification
	Some pieces of scrap too large	Bridging and uneven melting	Variable metal temperature and composition
	Non-ferrous parts containing lead, aluminium, etc. not removed from bought scrap Delivery of heavily painted scrap accepted into stockyard Excess of vitreous enamelled scrap in each charge	Contamination of the metal with: aluminium lead boron antimony	Pinhole defects Serious loss of strength Cracking Chill and increased hardness Increased hardness
	Gas works scrap accepted	High sulphur iron	Chilled edges and sections Top-surface blowholes
Steel scrap	Grade and unwanted contaminants not specified on purchase order Insufficient vigilance to detect and eliminate: pieces of sulphur-bearing or leaded free-cutting steel pieces of non-ferrous metal in baled/fragmented scrap heavily painted scrap pieces of stainless steel	Contamination of the metal with: aluminium sulphur lead chromium	Pinhole defects Chill and top-surface blowholes Serious loss of strength Cracking Chill and increased hardness
	Pieces larger than 1/3 cupola size	Bridging and uneven melting	Variable metal temperature and composition
Non-ferrous alloy scrap	Free-cutting copper scrap containing tellurium Nickel/copper alloy scrap containing lead, aluminium and leaded-bronze inserts	Contamination of metal with: tellurium lead aluminium	Chilled sections Serious loss of strength or cracking Pinhole defects
Ferro-alloys inoculants, carburisers	Composition and grading requirements not adequately specified on purchase order Failure to check container labels against advice note information Materials not clearly labelled or segregated in the stores	Ferro-alloy pieces too large, not dissolved Incorrect materials used	Hard spots on machining Metal not to specification
	Materials not kept dry	Moisture pick-up	Pinhole defects
	No laboratory checking of materials against specification, e.g. aluminium in ferrosilicon	Aluminium contamination	
	Variations in sulphur and nitrogen contents of carburisers	Variable content of sulphur and variation in response to inoculation treatment Variable content of nitrogen	Chill, or poor graphite structures Fissure defects Variation in tensile strength and hardness
Coke	No action taken to avoid the use of small coke, i.e. below a mean size of 9 cm	Reduced melting rate and lower metal temperature, unless blast increased	
	No periodic laboratory checking for quality, e.g. sulphur and ash contents	Sulphur and carbon pick-up vary	Top-surface blowdown

4.3.2 Coke Quality

The quality of the coke used has a direct bearing on the efficiency of cupola operations and a particular effect on metal temperature, carbon pick-up and the sulphur content of the iron. Foundries need to give careful consideration to several parameters:

- The fixed carbon content of a coke is calculated by deducting from 100 the sum of the percentage moisture content, the ash content and the volatile matter of the analysed sample. The higher the fixed carbon content, the higher the calorific value and the better the value for money.
- Moisture in the coke despatched from the coke oven reduces the weight of carbon available per tonne and is, therefore, undesirable. In addition, some of the calorific value of the fixed carbon will be lost in boiling off the water and superheating the resulting steam. At the same time, however, the industry needs to recognise the necessity for the coke to contain some moisture to avoid fires on conveyor belts and in lorries and wagons.
- A high ash content is undesirable as it reduces the fixed carbon content – and, therefore, the calorific value – of the coke and generates a greater volume of slag in the cupola.
- Volatile matter is undesirable as it reduces the fixed carbon content – and, therefore, the calorific value – of the coke.
- The size of foundry coke directly affects both coke consumption per tonne of iron melted and the melting rate. An average coke size of 90 mm appears to provide the best result. Foundries should avoid using fine coke as this reduces both the melting rate and metal temperatures (Fig 14). Fine coke also necessitates an increase in blast pressure to ensure delivery of a given volume of air, and this may be beyond the capability of the existing blowing equipment. However, increasing coke size above 90 mm has no beneficial effect. This is probably because large pieces of coke tend to be fissured and to break easily both during handling and charging and as a result of charge impacts within the cupola shaft. Large, heavily fissured coke can cause a deterioration in furnace performance.
- Sulphur is an undesirable element in cast iron, and the aim should be to use cokes with as low a sulphur content as possible. However, the sulphur content of coke depends on the sulphur content of the coal feedstock.

The following are typical properties for Welsh foundry coke:

Moisture	1.6% max
Ash	7.5% max
Volatile matter	0.5% max
Sulphur	0.72% max
50 mm shatter index	97
Mean size (despatched)	147 mm
M80 Micum index	75

NB: The Micum test is an empirical test intended to simulate the effect of both dropping pieces of coke and rubbing them against each other or against a hard surface, as occurs during handling and transportation. The resulting Micum index gives an indication of the strength of the coke and its resistance to abrasion.

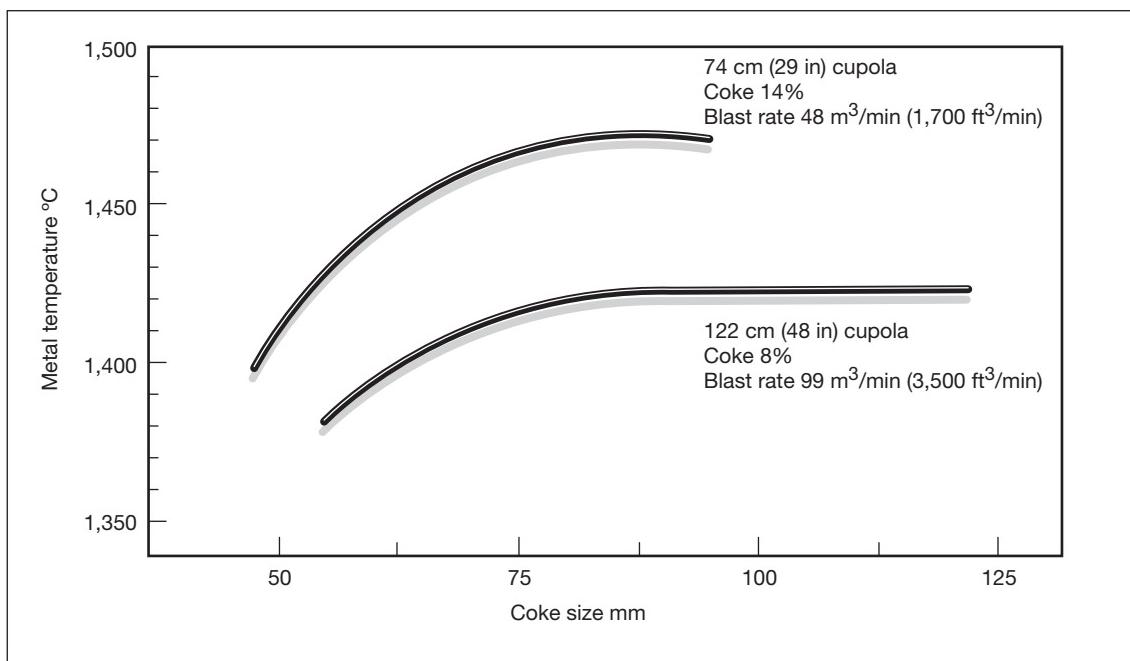


Fig 14 The effect of coke size on metal temperature

4.4 Coke Bed Preparation

Cupola coke bed preparation is a vital function governing metal temperature and melting rate during the early part of the melt. Low temperatures caused by an inadequate bed height usually take more than one hour to correct once the melt has started.

Once steady melting conditions have been attained, the operating height of the coke bed is determined by the amount of charge coke, the blast rate and the character of the stock in the cupola. These factors vary widely and so there is no general rule for the correct initial bed height. The most satisfactory height must be determined by experiment for each cupola and operating condition. This is achieved by starting with a bed height that is expected to be too great and reducing it on subsequent melts in 80 mm steps, until the lowest acceptable metal temperature is reached. If the metal temperature is too low during the first melt, then the height of the bed must be increased.

In practice, with cold blast cupola operation, a bed height of 1 m above the tuyères (the upper row in a divided blast operation) is typically the minimum height that can be employed. Where a high metal temperature or a high carbon pick-up is required, involving large coke charges, a bed height of 1.3 – 1.5 m above the tuyères may be necessary. This applies either when melting charges with a high steel content or when producing malleable iron and grey iron for automobile castings.

Several stages can be identified in correct coke bed preparation:

- 1 Select the largest coke with the fewest fissures that is available.
- 2 Position a gas/air (or oil/air) torch a few inches above the sand bottom on a support of coke, with the jet near the centre of the cupola.
- 3 Build up the coke bed to just below the tuyère level.
- 4 Close the tuyère cover plates and ignite the coke using the torch. Do not use wood or an oily rag.
- 5 Check for uniform coke ignition across the cupola by inspection through the tuyère sight holes. When the coke has ignited uniformly, open the tuyère cover plates.
- 6 Add coke through the charging door in several batches, allowing each to burn through uniformly before adding more.

- 7 Close the tuyère cover plates and complete bed ignition by blowing for a few minutes using the cupola blower at a gentle blowing rate. This operation also pre-heats the taphole and is useful where the time available for bed preparation is limited.
- 8 Turn off the blower and open the tuyère cover plates. Using an iron bar, poke the bed through the tuyères to close any voids and thus consolidate the bed.
- 9 Measure the bed height with a calibrated gauge rod, or a plate and chain, and add coke through the charging door to bring the bed to the required height. A layer of between 230 – 300 mm of coke is usually needed. Re-measure the bed height.

The practice of adding a layer of cold coke allows the coke to burn through while charging is proceeding and assists the production of hot metal at the start of the melt. It also avoids melting charge materials while filling the cupola and the possible production of a hard taphole.

4.5 Lining Practice

4.5.1 Lining Problems and the Need for Repair

Optimum melting conditions are obtained when the cupola is blown at or near the optimum specific blast rate (see Section 3.2). However, as melting proceeds, the diameter and area of the melting zone increase as a result of lining erosion and wear. This results in less than optimum operation.

Minimising lining attack is, therefore, an energy efficient measure. This can be achieved by ensuring the correct installation and condition of the lining material. Improvements in the refractory properties of lining materials have been achieved in recent years, and the combination of a low-cement castable material under a working lining of siliceous gunning material has proved beneficial, enabling longer melting campaigns to be undertaken. Good quality bricks with an alumina content of 40% are adequate for lining the melting zone of a cupola. It is not necessary to use more expensive bricks with a higher alumina content.

During the melting process, burn-back occurs above the tuyères in the melting zone. This burn-back is generally considerably greater during the first melt in a newly bricked cupola than during subsequent normal operation. Repair should be by conventional patching and slow drying. Rebricking is not necessary.

During normal operation, the extent of burn-back increases with the duration of the melt and the temperature of the melting zone. It is also increased by excessive blast, excessive flux, high steel charges, incorrect tuyère dimensions and uneven charge distribution.

Satisfactory and economic cupola operation requires the melting zone to be efficiently repaired after each melt. Inefficient repair can cause problems:

- The formation of viscous slag, which is readily chilled in the tuyère areas, causes the tuyères to become slagged over during the melt.
- Bridging of the charge above the tuyères can occur, particularly if a section of the lining slides, slumps or spalls. This reduces cupola efficiency and, in severe instances, can stop the melting process altogether.
- A hot spot appears on the cupola shell during the melt.
- The cupola requires rebricking or relining only a short time after the installation of a new lining.
- When melting zone diameter has been allowed to increase, additional coke must be added to return the bed to the required height.

4.5.2 Lining Repair Techniques

Ganister patching

Ganister patching requires:

- the removal, by chipping, of slag and coke attached to the lining as these will prevent the patching material from adhering to the furnace wall;
- the provision of just enough moisture to make the patching material plastic and workable;
- the slow drying out of the repair work to ensure that the patching material does not become detached soon after the melt commences.

Pneumatic gun patching

Monolithic patching material applied by pneumatic gun is generally used for cupolas with a diameter of more than 950 mm. This technique reduces patching time, labour requirements and material costs but gives consistent and satisfactory results. Pneumatic gun patching requires:

- the removal, as for ganister patching, of slag and coke attached to the cupola wall (it is not necessary to roughen glazed surfaces as this patching material will adhere to such surfaces);
- the provision of a ledge to support the patch, because of the low strength of the refractory: the method used to provide this ledge will depend on the extent of burn-back, but a row of bricks immediately above the tuyères may be necessary;
- a moisture level in the material that is sufficient to reduce rebound and dust but not too great or too variable to result in spalling;
- application of the patching material at right angles to the refractory surface using a progressive circular motion: this will minimise rebound;
- the operator to stay above the work, shooting downwards from scaffolding or a telescopic platform and building up the lining progressively from the tuyères (Fig 15): this will prevent spalling of the lining.

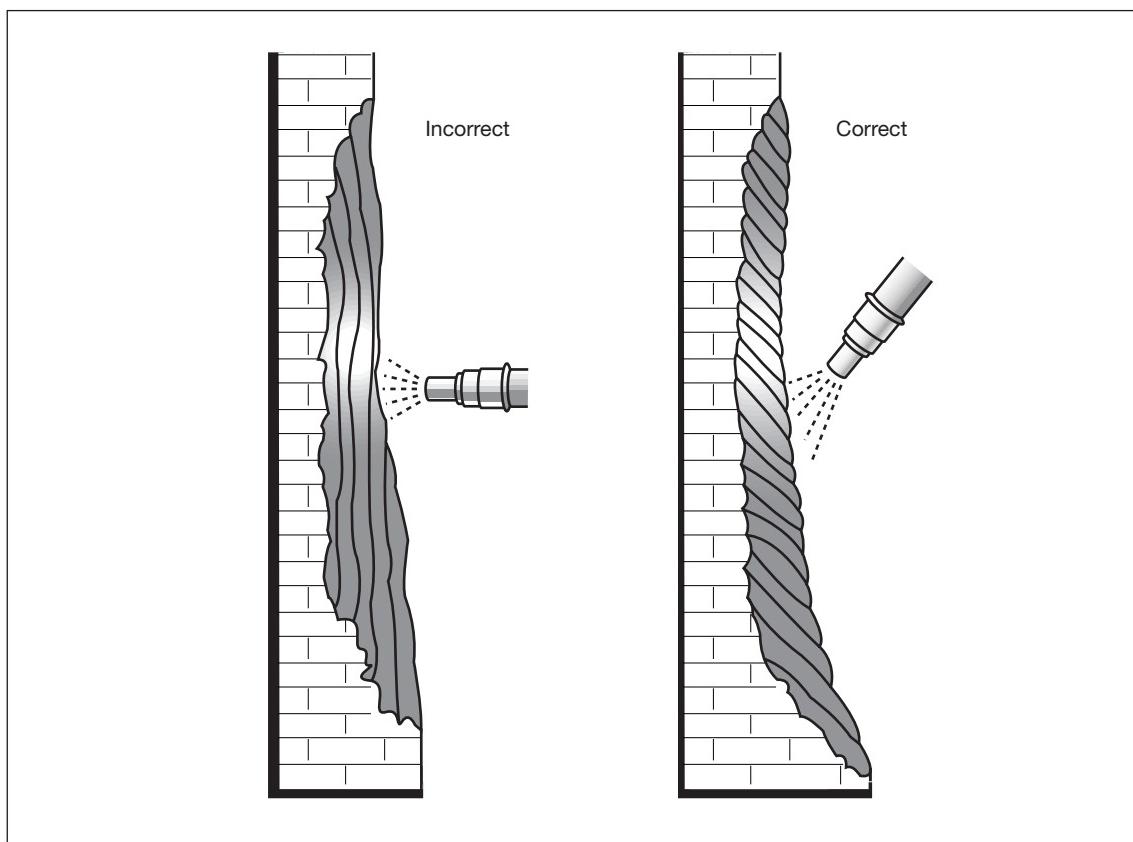


Fig 15 Lining repair techniques

4.6 Fluxing Practice

Flux additions ensure that the slag (which consists of coke, ash, rust, dirt and eroded refractory) is sufficiently fluid to separate from the iron and flow freely from the cupola. Consistently smooth cupola operation can only be achieved if the flux addition is correct.

The most commonly used flux is limestone (calcium carbonate), which calcines in the cupola shaft to form lime, a basic oxide. The lime then combines with the other slag-forming constituents, which are mainly acidic in character, to provide a fluid slag. Another flux used is dolomite (calcium-magnesium carbonate), which calcines to a mixture of lime and magnesium and has a fluxing action similar to that of lime alone.

The limestone or dolomite used for fluxing purposes should have a calcium carbonate/magnesium carbonate content of at least 96% and a silicon and other impurity content of less than 4%. The material should be between about 2.5 – 7.5 cm in size.

Slags can be classified according to the degree of basicity (expressed in terms of $[CaO\% + MgO\%]/SiO_2\%$):

Mild basicity:	1 – 2
Moderate basicity:	2 – 3
High basicity:	> 3

High slag basicity will produce iron with a high total carbon content, a low sulphur content – as required for ductile iron production – and a high silicon melting loss. The reverse is true for slag with a low basicity. Fluorspar is usually added to slags with a high basicity at the rate of 0.5 – 3.5% to ensure a sufficiently fluid slag.

Most cupolas are operated with a slag basicity of less than 1 (acid slag), because basic slag cupola melting has certain disadvantages:

- high silicon losses;
- high refractory costs;
- higher fluxing material costs;
- greater difficulty in controlling metal composition than in acid cupola melting.

4.6.1 Flux Requirements for Acid-lined Cupolas

The amount of limestone (or dolomite) required for acid cupola melting depends on the cleanliness of the charge materials, the amount of coke ash to be flushed and the extent of lining erosion. A normal addition is 3 – 4% of the metal charge weight, although very dirty charge materials may require more.

If too little limestone or dolomite is added, the slag generated is thick and viscous. This can:

- choke the spaces between the charge materials;
- coat the coke, thereby interfering with the carbon pick-up mechanism;
- cause bridging in the area chilled by air from the tuyères;
- make it difficult to tap from the furnace.

In extreme cases, gas bubbles may become entrapped in the viscous slag causing it to foam inside the cupola. If it rises and flows into the tuyères, it creates serious bridging problems.

4.6.2 The Importance of Correct Flux Addition

Many foundries pay too little attention to the weight of flux additions, even when the other elements of the charge are correctly calculated and weighed and the blast-rate is controlled. In some cases, a few shovels of limestone are carelessly thrown into the charging bucket or skip. The use of a small portable scale, or a container marked to hold a known weight of flux, will ensure that the correct quantity is added, thereby controlling slag formation and basicity, and helping to ensure trouble-free cupola operation.

4.6.3 Flux Addition to the Coke Bed

During the early part of the melt, approximately four times the normal limestone or dolomite charge should be added to the coke bed before charging begins. This will flux ash from the bed and restrict the pick-up of sulphur by the metal.

4.6.4 Supplementary Fluxes in Acid Slag Operation

It is possible to supplement or partly replace the limestone or dolomite with fluxes such as fluorspar or sodium carbonate (soda-ash), both normally in briquette form, and lump calcium carbide. This aids the formation of a fluid slag. However, supplementary fluxes may be expensive and their use may, under certain conditions, affect carbon pick-up. They should not be used to correct poor slag conditions arising from the incorrect use, or inadequate control, of the primary fluxing process.

4.7 Materials Handling and Cupola Charging Systems

4.7.1 Materials Handling

Materials handling is a major factor in the efficient operation of the melting process. It covers the entire process from receipt of the charge materials to distribution of the molten metal, and it must include the identification and separation of materials according to type and chemical composition. The segregation of materials must be arranged to provide free flow and to minimise the need for double handling. A facility for reducing materials to the size required for charging may also be required.

Overhead or mobile magnet cranes are commonly used throughout the industry to handle the charge materials.

4.7.2 Cupola Charging Systems

Excessive coke consumption and/or an inability to attain the desired tapping temperature can often result from lack of control in the weighing of charge materials.

The practice of charging coke by volume is prone to error as variations in coke size and packing density can occur. Rough handling can affect the size of coke through degradation. In addition, allowing the coke to be exposed to rain water will give rise to errors in the effective coke charge.

Modern cupola charging systems incorporate automatic weight-recording facilities based on load cells and microprocessor control. The ability to inspect individual charge element weights, and accumulated totals, greatly helps the melting control process. Computer control is also used to even out charge variations, enhancing the consistency of cupola operation.

Charge level control is vital.

Maintaining a full cupola during operation:

- reduces the variation in metal temperature;
- reduces the quantity of scrap generated as a result of the molten metal being insufficiently superheated to produce adequate castings.

If a cupola is overcharged:

- the charge bucket may jam in the cupola;
- the charge may stick in the charge chute;
- material may be ejected from the charge hole and create a danger to operators below;
- after-burners may be damaged by being covered with charge materials;
- combustion in the stack above the charge hole may not take place.

If a cupola is undercharged:

- reduced pre-heating times will cause metal temperatures to fall;
- the greater drop will cause more degradation of the coke, which may lead to a further reduction in metal temperature.

A cupola that has a mechanical charging system, but is operated from a position in which the charge level cannot be observed, would benefit from the installation of a charge-level indicator. This may be interlocked with the charging equipment, so that it automatically initiates the cycle when the stock level in the cupola drops and a charge is ready for hoisting. The cost of installing a charge-level indicator will usually be readily recovered by the reduction in cupola down-time and the lower levels of scrap associated with better control of metal temperature.

Only in cupolas that are hand-charged, or have operators present on the charging platform, is there less need to fit charge-level indicators.

4.8 Metal Distribution

Energy is wasted if:

- the metal supplied is too hot and has to be cooled before pouring to prevent defects associated with internal shrinkage;
- the molten metal transfer system allows an excessive loss of metal temperature between furnace tapping and mould pouring, thereby causing castings to be rejected for cold-metal defects such as mis-runs, blows and laps.

Most foundries can accommodate metal temperature losses between the melting furnace and mould pouring of up to 100°C. However, many foundries experience distribution losses approaching 200°C by the time the moulds are poured and compensate by operating their melting process at a higher temperature. The potential for reducing energy costs is much greater in these foundries than in units with a smaller temperature loss.

The implications of high metal temperature losses are more critical in cupola melting than in electric melting. Typically, to increase metal temperature by 50°C in an electric melting furnace, there must be an input of approximately 24 kWh/tonne of molten iron: to achieve the same temperature increase in a cupola, the coke input must be increased by 5% for a given weight of metal. At an electricity cost of 4.5p/kWh, the cost of superheating 20 tonnes of iron per day through 50°C in an electric furnace would cost £4,900/year: the equivalent cost for cupola melting would be about £28,750/year (assuming a coke cost of £150/tonne).

Energy efficiency is a vital factor in controlling operating costs and there are a number of areas relating to holding and metal distribution that offer potential energy cost savings. These include:

- the design of the furnace launder systems;
- ladle practice;
- the use of insulating covers for launders/ladles;

- effective pre-heating of launders/ladles;
- eliminating unnecessary ladle transfer operations;
- rapid metal distribution;
- temperature control.

The following Energy Efficiency Best Practice Programme Good Practice Guides, available from ETSU, provide additional information on this subject:

- PGP 17 *Achieving High Yields in Iron Foundries*
PGP 63 *Metal Distribution and Handling*
PGP 68 *Holding Metal at Elevated Temperatures*

Checklist for Effective Operational Control

- Measure and control the air-blast volume using an air weight controller.
- Minimise blast-off periods.
- Use effective programming to balance metal supply and demand.
- Avoid unnecessary superheating of the iron.
- Measure and control coke bed height.
- Do not light the bed too early.
- Weigh all charge materials.
- Reject all coke <50 mm in size.
- Recover usable coke from the ‘drop’.

5. EXTERNAL TREATMENTS AS AN AID TO EFFICIENT CUPOLA MELTING

5.1 Background

The cupola will accept a wide range of charge materials and will produce molten iron within acceptable compositional limits as long as the operation is properly controlled. However, to achieve the most economic performance in terms of overall melting cost and energy consumption, there must be operational consistency and continuity together with stable melting conditions. In most cases, a conventional cupola operating under acid slag conditions will provide low-cost molten metal for the production of grey iron castings. It will also, with the proper external treatments, provide base iron for the production of ductile and low alloy grades.

Two of the most important metal treatment processes in the iron foundry industry are carburisation and desulphurisation. There are several reasons for this importance:

- These processes allow irons of a given grade or composition to be produced from cheaper raw materials. The application of desulphurisation techniques makes it possible to replace a proportion of pig iron in the charge with cast iron scrap. Similarly, the use of carburisation, perhaps also with desulphurisation, allows the replacement of some pig iron with steel scrap.
- In the production of nodular irons, the higher the sulphur content before treatment the greater the quantity of alloy that must be added. Reducing the sulphur content of the iron to a low level before treatment allows substantial alloy savings to be achieved and avoids the defects caused by the inclusion of dross in castings.
- A foundry with the ability to carburise and desulphurise iron has the flexibility to produce several different grades of iron from the same basic cupola charge mixture.

5.2 Metal Treatment Processes

Several processes have been developed that allow consistent carburisation and desulphurisation of cast iron to the desired levels. The main carburisation procedures involve injection into the cupola, and this is generally carried out through the tuyères. The fine carbon particles are brought into contact with the molten metal droplets, thereby creating a high surface area to volume contact and creating optimum conditions for the absorption of carbon. Many, if not all, of the true external processes rely on creating turbulence within the molten metal to achieve contact between the reactant and the metal, thereby increasing both reaction rates and efficiencies.

5.2.1 *Tuyère Injection*

A continuous stream of re-carburising material is injected through a lance directly into the cupola via one or more tuyères (Fig 16). Particle size is critical: this should ensure a sufficient volume of carbon without being too large to prevent rapid absorption.

The equipment consists of a storage hopper and a feed injector, the latter providing a continuous supply of material to the primary injector. The latter is mounted on load cells and monitors the continuous flow of material to the injection lances. The system is linked directly to the cupola blast and functions only in a ‘blast-on’ condition.

The percentage carbon recovery that can be achieved depends on the temperature and base composition of the metal. Pick-up declines as the eutectic composition of maximum carbon solubility is approached.

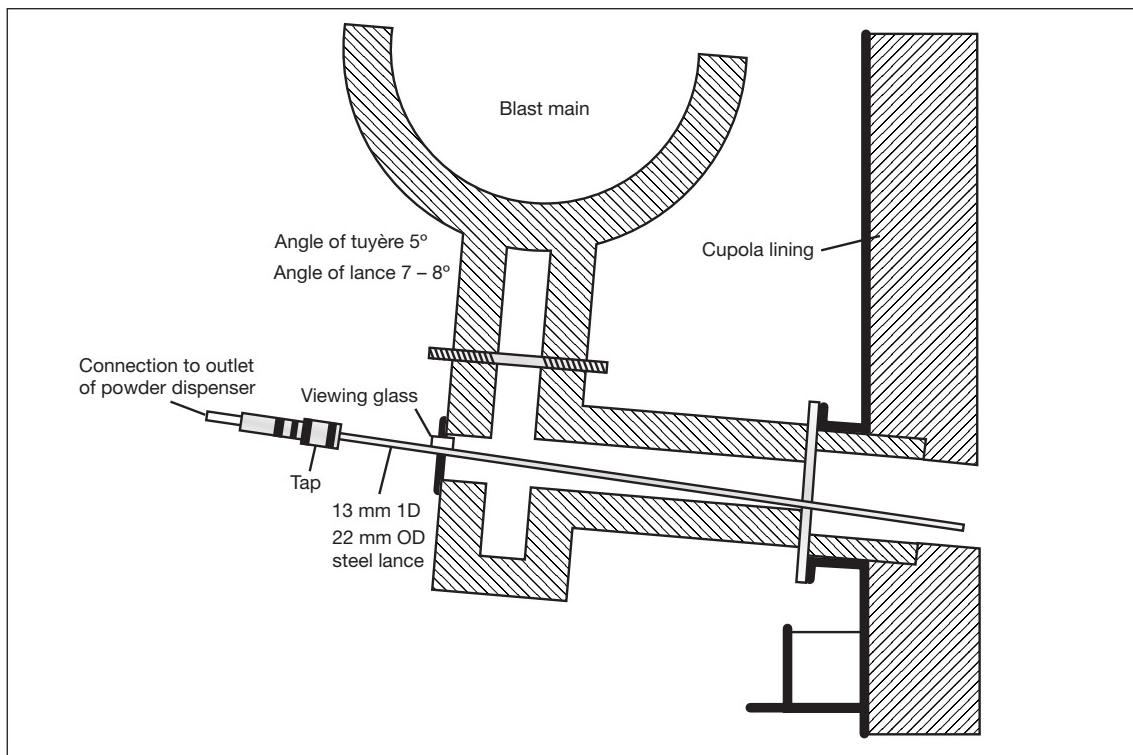


Fig 16 Tuyère injection for metal treatment

5.2.2 Porous Plug Ladle

The porous plug ladle is a low-cost method of agitating the metal during carburisation and desulphurisation. The ladle is filled with molten metal to about two-thirds of its capacity, and the desulphurising and carburising additions are made either prior to, or at any time during, this process. Compressed air or nitrogen is then passed through a porous plug in the bottom of the ladle at a flow rate of approximately $0.14 - 0.23 \text{ m}^3/\text{minute}$. This creates a vigorous stirring action which improves the efficiency of the metallurgical reactions. A treatment time of 2 – 4 minutes is normally required. Providing the ladle with a refractory cover reduces metal spillage and temperature loss.

The normal way of treating cupola melted metal in a porous plug ladle is to place the desulphurising and carburising agents in the ladle and then tap continuously on to them. Blowing begins once the ladle is about one-third full, so that treatment is almost complete by the time the ladle is full. This reduces standing time and, therefore, temperature loss. The short treatment time involved means that it is not usually necessary to treat large quantities (more than ten tonnes) of metal at any one time.

Adding 1% calcium carbide to a porous plug ladle allows foundry operators to achieve carbon pick-up levels of 80 – 90% and to reduce the sulphur content of the metal to 0.01% or lower from a starting point of 0.1%.

Initially, poor plug design limited the application of this technique. The plugs were rigidly fixed into the ladle bottom, and considerable time and labour was required for their (frequent) replacement. A design has now been introduced that allows the porous plug to be rapidly and simply extracted and replaced with a new plug. Replacement takes place after about ten treatments, and plug life can be increased by using nitrogen gas for the metal treatment rather than compressed air.

Porous plug use has recently been extended to a continuous treatment process operating in conjunction with an acid-lined cupola. A number of foundries use this system to reduce sulphur levels during grey iron production, but the high degree of carburisation and desulphurisation that can be achieved means that most installations produce low-sulphur iron for nodular iron production.

The low cost of the porous plug ladle process means that it is favoured by small to medium size foundries.

5.2.3 *Shaking Ladle*

Another important technique for iron carburisation and desulphurisation is the shaking ladle, which was originally developed in Sweden. This consists of a specially designed ladle that is mounted in a framework and subjected to a rotary motion. The motion imparted to the ladle and its contents is analogous to stirring a cup of tea to dissolve the sugar. However, with the shaking ladle, the speed of rotation and the degree of eccentricity are critical to obtaining the correct wave motion within the ladle.

Operators can achieve a high degree of desulphurisation using the shaking ladle, and the process requires about 1% of carbide to reduce sulphur to the low level required in nodular iron production. A shaking time of 4 – 6 minutes gives the best results. Other additions can also be made to adjust metal composition.

The high cost of shaking ladle equipment limits its application to large foundries producing nodular iron, ingot moulds and refined irons.

6. ENVIRONMENTAL CONTROLS

6.1 Background

Introduction of the Environmental Protection Act (EPA) in 1990 and its impact on the control of emissions from melting plant has caused all foundries to review their existing activities. In the case of non-compliance, companies were required to produce an action plan, to be implemented within a given timescale.

All but the lowest-volume producers have been faced with the high cost of installing appropriate abatement equipment or adopting a ‘cleaner’ melting process. A significant number of foundries have taken the opportunity of replacing their cupola plant with electric melting. Similarly, those companies wishing to expand their existing melting capability, or to develop a greenfield site, have generally been persuaded to follow the electric melting option, with its lower emissions.

Until recently, hot blast cupolas were an economic proposition only for UK foundries with large continuous requirements for molten iron. These units offered high levels of energy efficiency and low operating costs. However, hot blast units came under the control of the Alkali Inspectorate and had to comply with a stringent emission limit of 115 mg/m³, which required the installation of high efficiency filtration equipment. As the same limits were not imposed on cold blast units, the capital costs associated with hot blast cupolas were prohibitively high for all but the largest operators.

With the advent of statutory emissions limits under the EPA (1990), all future cupola melting installations, irrespective of the melting technique employed, will need to be equipped with high efficiency filtration systems. Thus, the cost premium previously associated with hot blast units has been eliminated, and the economic justification for hot blast units can be extended to smaller installations.

6.2 Statutory Requirements

6.2.1 Environmental Protection Act

The EPA placed statutory limits on particulate emissions from both hot and cold blast cupolas, and called for compliance by April 1997. The statutory limits that must be achieved by existing plant (except cupolas with melting rates below 4 tonnes/hour) are 115 mg/m³ if the plant was fitted with arrestment equipment prior to the Act, or 100 mg/m³ for all other plant. Cupolas with nominal melting rates of less than 4 tonnes/hour must be fitted with simple wet grit arresters.

Requirements under the Act are subject to regular review, and the Department of the Environment, Transport and the Regions (DETR) has issued revised Secretary of State’s Guidance (notes) – Hot and Cold Blast Cupolas – PG 2/5(96) March 1996. Clause 17 of these notes covers emission limits and compliance dates, as detailed below:

- 17(a) For all hot and cold blast cupolas the concentration of total particulate matter emissions into the air should not exceed 20 mg/m³ after 1 April 1997, except in the cases (b), (c) and (d) below.

- 17(b) For hot and cold blast cupolas which have installed abatement equipment, or which are the subject of a contract for the supply of abatement equipment, which meets an emission limit of 100 mg/m³ or 115 mg/m³ (but not 20 mg/m³), the limit of 100 mg/m³ or 115 mg/m³ (as appropriate) should apply until 1 April 2010, after which clause 17(a) should apply.

- 17(c) For hot and cold blast cupolas where the average actual production rate per 24-hour day when one or more of the cupolas is operated (as averaged over a calendar year) is more than 20 tonnes of metal melted, and which have a melting capacity of less than 4 tonnes per hour and which are not described in Clause 17(b), simple wet arrestment (or other arrestment equipment with at least the same efficiency) should be installed and operated until 1 April 2003, after which Clause 17(a) should apply.
- 17(d) For hot and cold blast cupolas where the average actual production rate per 24-hour day when one or more of the cupolas is operated (as averaged over a calendar year) is 20 tonnes or less of metal melted, and which are not described in Clause 17(b), simple wet arrestment (or other arrestment equipment with at least the same efficiency) should be installed and operated by 1 April 1997.

The Guidance notes also call for smoke emission during normal operation not to exceed the equivalent of Ringelmann Shade 1 as described in the British Standard BS 2742:1969. In the case of lighting up, smoke emissions should at no time exceed Ringelmann Shade 2 and should not exceed Shade 1 for more than 15 minutes.

It is a mandatory requirement that emission tests are carried out by the foundry at regular intervals. The need for and scope of this testing and the frequency and time of sampling will depend on local circumstances, operational practice and the scale of the operation. Local enforcing authorities must be informed of the times and dates of monitoring to determine compliance and must be notified of test results.

Continuous emissions monitoring is also required. This is not intended to give numerical emission values but to indicate relative performance and/or process variations.

In the past, many cupolas have been equipped with various types of wet scrubber for gas cleaning. These systems need very high power inputs to clean the gases to particulate concentrations of less than 100 mg/m³. Pin-type rotary disintegrators have been quite widely used on hot blast cupolas and on other cupolas with off-takes below the charge level. Electrostatic precipitators have also been installed but, while these have a low energy consumption, they are unsuited to the variable gas flows and dust and fume loadings associated with cupola operation.

6.2.2 *Integrated Pollution Prevention and Control (IPPC)*

The European Commission has introduced an IPPC Directive which effectively requires prescribed processes to apply best available techniques (BAT) control to releases to air, water and land. The Directive is similar to the UK IPC (Schedule A) legislation, but covers energy efficiency, noise and vibration, and as is common with other European environmental directives, places considerable emphasis on waste minimisation.

The Directive was adopted in October 1996 and has to be incorporated into the legislation of each Member State within three years of adoption. This will be accomplished in the UK by October 1999. New processes will be required to comply with the Directive as soon as the state legislation is passed. Existing processes will have up to eight years more to complete upgrading to the standards required.

This new legislation will be applied to all European Union ferrous foundries with a production capacity exceeding 20 tonnes/day of finished castings and to non-ferrous foundries with a capacity exceeding 4 tonnes/day for lead and 20 tonnes/day for all other metals.

Technically, this will place approximately 110 foundries under Schedule A – HMIP control and the Guidance Notes issued by HMIP for control of emissions from such foundries are significantly more rigorous than for the Schedule B control regime. The control regime for such foundries will be through local authorities with support from the Environment Agency (EA).

It is likely, therefore, that the Directive will have only a relatively minor impact on the legal control on foundries, but if the foundries have to meet the control levels promoted in the EA Guidance Notes for foundry processes (i.e. IPR 2/1 and IPR 2/2), then costs for many of the medium-sized foundries will increase substantially. The degree of control, including record keeping, monitoring frequency and some emission limits, would be expected to be considerably tighter than for the current situation under local authority control of air pollution.

6.3 Designing Cupolas for Effective Environmental Operation: The Problems

The special requirements associated with the control of cupola emissions makes the design of effective systems more difficult for cupolas than for other foundry processes. The principal reasons can be summarised as follows:

- Cupola gases range in temperature from 100 – 1,200°C during the melting process.
- Particle sizes range from less than 1 µm in the case of smoke and fume to up to 10 mm pieces in the case of coke.
- Smoke may contain uncombusted volatile matter, and this may condense on to the filter media.
- The sulphur dioxide (SO₂) content, although low, can cause corrosion in wet scrubbing systems or in dry filtration units operating below their dew point temperature.
- High flow rates may be associated with the ingress of dilution air at the cupola charge opening. Cupola blast conditions can also cause substantial variations in the volume of gases to be cleaned.
- Cupola exhaust gases contain a high proportion of CO (approximately 10 – 15%) at the top of the charge under normal operating conditions. Unless this gas is burned it can be poisonous to workers, can cause explosions in fume collection systems and is generally regarded as an unacceptable discharge.
- The generation of smoke, vapour and odours depends on the cleanliness of the charge materials.

6.4 Fume Cleaning Options

6.4.1 Dry Filtration

Most modern systems for cupola fume cleaning are based on the use of bag filters. Dry filtration relies on a basic mechanism whereby a filter cake or bed is formed on the surface of a fabric sleeve by the dust and fume being collected. Over time, the pressure drop across the filter increases, reducing its cleaning efficiency. Eventually, the design limits of the system are exceeded, at which point the cake must be removed from the filter fabric to restore collection efficiency. Removal is achieved either by shaking the filter cloth or by pneumatic pulsing. The dust is then removed for disposal to waste.

In cold blast operation, the off-take gas temperature of a cupola throughout its operating cycle can vary between about 600°C and 1,200°C. These temperatures are higher than can be tolerated by conventional fabric filter materials. All dry systems must, therefore, incorporate cupola gas cooling to a temperature that is low enough to prevent damage to the filter media but not too low to cause the condensation of volatile matter and, ultimately, water on the filter. Such condensation has three serious and deleterious effects:

- filter bags become ‘blinded’ and cannot be cleaned;
- there is a danger of flammable deposits igniting, causing fire or explosion;
- ductwork, filter cases and fan systems are likely to corrode.

In recuperative hot blast systems, the flammable off-take gases are generally burned to provide heat to the blast air via a heat exchanger, thereby allowing a reduction in coke use.

6.4.2 Wet Scrubbing

High efficiency wet scrubbing systems, such as rotary disintegrators (Thiesen system) or high energy venturi units, can be used to clean hot gases prior to combustion. These systems have been widely used in hot blast cupola installations over the last 40 years and have achieved cleaning efficiencies allowing compliance with Alkali Inspectorate requirements for this type of cupola (115 mg/m^3 particulate emission). Furthermore, wet scrubbers are reliable and are capable of maintaining cupola emissions at levels below 100 mg/m^3 for a reasonable power input. Higher cleaning efficiencies require much larger power units and are economically unattractive. Such systems are, therefore, unlikely to be used to achieve emission levels below 20 mg/m^3 .

The high energy content of cupola waste gases means that, even where blast heating systems achieve blast temperatures of $500 - 600^\circ\text{C}$, about 50% of the available energy content will be discharged after the recuperator in the waste gas. Fitting scrubbers before the recuperator allows this gas to be flamed and vented to atmosphere: where there is no adequate pre-cleaning, the recuperator exhaust must, of necessity, be cooled and filtered.

Wet scrubbing systems generate a waste sludge which must be treated. Treatment is generally carried out in settling tanks, and the resulting water is first chemically treated to control pH levels and then recirculated. The use of filter presses reduces the waste materials to a manageable cake.

6.4.3 Hot Blast Cupola Operation

In many modern hot blast cupola systems, particularly those produced in the USA, the gas off-takes are located above the charge door, even though this results in significant dilution of the gases evolved in the cupola shaft. Some designers consider this dilution to be acceptable as a high proportion of sensible energy is retained in the gases if they are quenched prior to combustion and are not saturated when burned. There are also claims that an off-take above the charge door is safer, as the CO-laden top gas can be more easily burned and the exhaust gas temperatures sustained above the CO auto-ignition point. At the temperatures achieved most volatile hydrocarbon materials in the fume will also combust in the presence of oxygen.

Self-cleaning, vertical shell-type recuperators are now becoming widely used on new hot blast cupola installations. These units are of relatively simple construction when compared with tube bundle type heat exchangers: any particulate matter will accumulate at the bottom of the shell, allowing ready collection and removal. Most recuperators of this type operate on the counterflow principal and have sufficiently effective heat transfer characteristics to achieve hot blast temperatures in excess of 500°C .

Although the latest Process Guidance Notes do not specifically require the combustion of the CO in cupola effluent gases, it is suggested that the afterburning of CO is essential to the performance of most dry filter systems. With fairly high coke charges (in excess of 10%), the CO content of the top gas is such that, combined with high temperature and sufficient air mixing, combustion will be virtually self-sustaining if the system is properly designed. In cold blast operation, combustion is best achieved by extending the shaft to enable a distance of about 2 m to be maintained between the top of the charge (at maximum level) and the charge door sill. Secondary air can then be injected above the charge level to maintain combustion. Gas burners would normally be fitted to aid combustion where carbon monoxide levels are low, but experienced operators claim that supplementary fuel requirements are very low.

In recent years, the introduction of the ‘cokeless cupola’ (see Section 7.2), which does not rely on coke as the primary fuel, has given rise to much reduced emission levels.

6.5 Energy Efficient Environmental Control

As outlined above, nearly all cupolas will need to be equipped with powered fume filtration systems if they are to comply with current and future environmental legislation. In many cases, provision will also need to be made for the combustion and incineration of effluent gases and organic fume. The energy requirements of these systems is significant, and both consumption and costs must be taken into account if melting system economics are to be optimised.

Most fume cleaning systems installed in the future will probably be based on dry fabric filters or on some method of screen cake filtration. One advantage of this type of unit is that power requirements are relatively low compared with those of high-efficiency wet scrubbers. To achieve a comparable cleaning performance, the latter will absorb about four times the energy of a dry fabric filter. Furthermore, wet scrubbers become uneconomical when cleaning is required to levels below 100 mg/m³. All filters to be installed will ultimately need to clean to a concentration below 20 mg/m³ to comply with national statutory requirements.

The need for high-efficiency gas cleaning systems on both cold and hot blast cupolas offers opportunities for waste heat recovery that cannot be ignored by any foundry operating such systems. The high temperature of the cupola exhaust gases following combustion means that they represent a high-grade heat source that, assuming pre-separation of the heavier particles in the gas stream, could effectively be used in either gas/air or gas/water heat exchange systems.

Possible applications for waste heat derived from a gas/air cooler include:

- space heating of workshop areas;
- charge material and coke drying systems;
- pre-heating bag filter outlet chimneys to prevent condensation when the ducting is cold;
- pre-heating dust extraction systems, shake-out drums, etc. to prevent condensation and sand build-up;
- the elimination of steam plumes from wet cleaning systems (venturi scrubbers etc.).

Potential uses for waste heat recovered from gas/water heat exchangers include domestic and plant hot water systems and water/air space heating units.

As melting plants generally operate concurrently with other production and administrative functions, the waste heat is available at useful times and there is no need for complex thermal storage systems, other than for hot water, in order to take effective advantage of the benefits provided by the heat recovery plant.

7. SPECIALISED CUPOLA OPERATING TECHNIQUES

In recent years, energy and environmental considerations have generated interest in a range of specialised operating technologies designed to enhance both the performance of the cupola and its environmental acceptability as an efficient melting unit. Many of these technologies are replicable and should be considered by any high-production iron foundry contemplating a new melting system. Some are potentially applicable to all cupolas and involve modification or retrofitting. Others require complete plant replacement. Several of the most promising of these new technologies are detailed below.

7.1 Supersonic Oxygen Injection

The use of supersonic oxygen injection is becoming an accepted technique, and several cupolas now apply this technology, both in the UK and in Europe.

The advantages of oxygen enrichment of cupola blast air are well understood (see Section 3.10) and most high-production foundries operate such a facility. In many cases, the oxygen is used not on a continuous basis but as an aid to metallurgical control, as a technique for facilitating start-up on a cold furnace, and as a means of increasing tapping temperatures as required.

Supersonic oxygen injection uses injection lances that are cooled by gaseous oxygen. These are mounted in the centre of each tuyère (generally water cooled) set back between 100 – 300 mm from the tuyère exit (Fig 17 overleaf). The following results are claimed:

- a reduction in blast volume;
- homogenised blast air/oxygen distribution and a reduction in internal furnace pressure;
- more even combustion across the bed, thereby reducing cupola heat losses;
- improvement in charge pre-heating – less temperature variation over the cupola cross-section;
- a reduction in charge-coke additions;
- a potential for melting rate variations of $\pm 50\%$ of the nominal melting rate;
- a reduction in exhaust gas volumes and in the amount of dust generated;
- reduced furnace shell losses with the higher temperatures achieved in the centre of the cupola;
- higher metal temperature;
- lower silicon losses;
- an increase in blast temperature because of the high off-take gas temperature (hot blast cupolas).

The process is claimed to be the first method of oxygen enrichment to demonstrate that, at a constant melting rate, the cost savings associated with the reduction in coke consumption fully compensate for the cost of the oxygen. It is also suggested that supersonic oxygen injection will allow the use of lower grade metallurgical coke, with consequent cost savings.

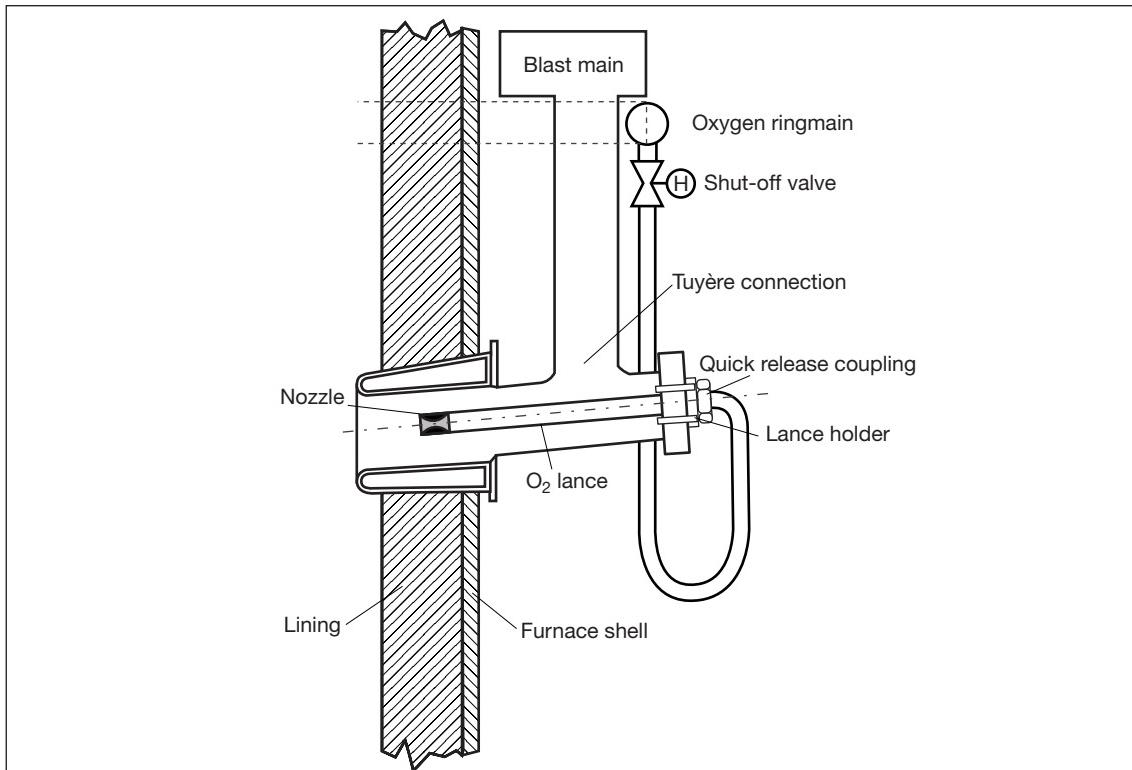


Fig 17 Supersonic oxygen injection

7.2 Cokeless Cupola Operation

The gas-fired ‘cokeless’ cupola has, for several years, offered an alternative to the conventional coke-fired furnace. It is a straight-shaft furnace with radially disposed gas burners sited in a similar position to the tuyères of a conventional coke-fired unit.

A water-cooled grate above burner level supports the bed material and the metallic charge. The bed material consists of refractory spheres approximately 175 mm in diameter and produced from a graphitised alumina-based refractory selected for its non-wetting properties. The initial bed is made up of several layers of these spheres and, when heated from below by the gas burners, becomes an effective heat exchanger. During the melting process the spheres are consumed at a rate of between 1% and 4% of the weight of metal melted, depending on the molten metal temperatures achieved. Bed renewal involves adding new spheres, as required, with the metallic charge.

The metallic charge is fluxed with limestone as in a conventional cold blast cupola. It is pre-heated by the products of combustion and melts as it comes into contact with the incandescent bed materials. The molten, superheated iron then falls through the water-cooled grate into the furnace well. Carburiser may be injected into the well of the cupola if required.

Tapping and slag removal from the cupola are carried out in a similar way to conventional cold blast cupola practice.

Because the charge contains no coke, the dust burden in the waste gases is much lower than in the gases from coke-fired units, although particulate emission levels are dependent on charge cleanliness.

The charge in a cokeless cupola normally requires a greater proportion of high-carbon materials than the charge in a coke-fired unit, and ferro-silicon may need to be added to raise silicon contents to the correct level. The use of low-sulphur charge metallics, e.g. high purity pig iron, and fuel will eliminate the need for external desulphurisation and provide a molten metal that is directly suitable for magnesium treatment for the production of ductile castings.

High tapping temperatures in a cokeless cupola cause a disproportionate increase in fuel consumption and a substantial increase in refractory sphere consumption. Normal practice is, therefore, to combine a cokeless primary melting furnace with an electric induction furnace and to use the latter for superheating, recarburisation and alloying (Fig 18).

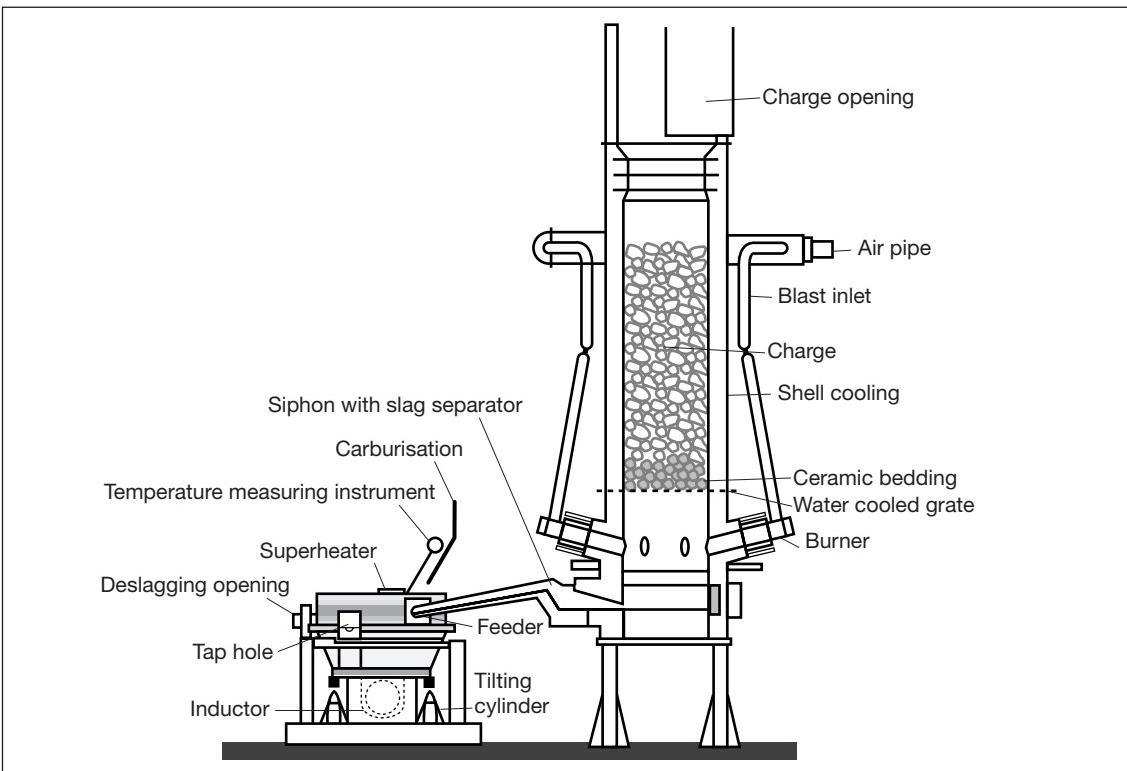


Fig 18 Duplexing with a cokeless cupola

About nine foundries in various parts of the world currently use the cokeless cupola as a primary melting unit. In areas where good quality carbon-bearing charge materials and natural gas or light fuel oil are readily available, it can provide a feasible alternative to more conventional melting methods.

7.3 Dust and Waste Injection Systems

The possibility of injecting both metallic and non-metallic particulate materials into the cupola furnace has been under investigation by foundries and equipment manufacturers for many years. Such a technique could be used for:

- re-melting swarf and borings;
- recycling waste materials, both metallic (e.g. shotblast fines) and non-metallic (e.g. flue ash, collector waste, used moulding sand and industrial sweepings);
- concentrating metallic effluents, e.g. zinc, for subsequent recovery.

The Environmental Protection Act requires polluters to assume start-to-finish responsibility for process waste and has stimulated interest in waste recovery and minimal disposal techniques. Furthermore, the high cost of energy and the realisation that many wastes can be used as low grade fuels, has raised the profile of materials recovery.

Most cupola injection systems are based on lancing through the tuyère. Using the same technique to inject dust and waste directly into the cupola has shown that these solid materials agglomerate in the cupola bed in the tuyère area and have a cooling effect. This restricts the rate at which continuous injection can take place and highlights the need for improved melting in these

locations and for the establishment of consistent cupola performance. Increasing continuous injection rates and establishing practicable feed rates for dusts arising as foundry wastes are, therefore, matters of major interest to cupola operators.

Recent development work has been carried out in both the UK and Germany to establish a technique for the continuous injection of substantial quantities of particulate material directly to a cupola. This is based on the use of oxy-fuel burners mounted in the cupola tuyères. Fuel (natural gas) and oxygen are fed to the burner head, while dust from a specially designed transporter unit is injected through the burner pipe and ejected at the burner outlet.

Oxy-fuel burners produce very high flame temperatures compared with fuel-air burners. The inclusion of an over-stoichiometric oxygen component increases the temperature of the coke bed in the area of the tuyère and speeds up melting of the materials introduced.

Trials involving the injection of different wastes into a cupola rated at 10 – 14 tonnes/hour are reported to have given the following injection rates:

- flue ash/cupola dust: 4 kg/minute via two burners;
- used moulding sand: 4 kg/minute via two burners;
- industrial sweepings: 6 kg/minute via two burners.

Each type of particulate contributes to the overall melting process in a different way. Flue ash, which contains approximately 15% carbon, and sweepings, which also contain combustibles, can be regarded as supplementary fuels. The zinc component of the flue ash can be concentrated in the filter cake and ultimately sold for zinc reclamation, a process that is said to be economic when the zinc concentration reaches 24%. Particulate matter may also be blended prior to injection.

The oxy-fuel burner is designed to minimise the energy requirement for heating, melting and superheating the cold stream of injection materials. It is also capable of being fired at higher rates to increase cupola flexibility. Furthermore, using oxy-fuel burners offers the same benefits as simple oxygen injection, such as a reduction in coke consumption, a reduced blast air requirement, and improvements in carbon pick-up and metal temperatures.

7.4 Blast Superheating from Auxiliary Energy Sources

The advantages of the hot blast cupola using recuperative or external blast heating to achieve combustion air temperatures of 500 – 600°C at the tuyères is well documented. Recent years have also seen a growing interest in the use of blast temperatures in excess of 700°C.

Very high blast temperatures improve recarburisation of the iron and allow lower blast rates for a given melting rate. Furthermore, the associated higher bed temperatures will result in less charge oxidation, allowing smaller charge pieces, e.g. borings, to be successfully re-melted. It has also been suggested that superheated hot blast systems will allow the use of lower grade, smaller metallurgical coke without incurring the reduction in tapping temperature that would occur in conventionally blown cupolas. Several overseas foundries are known to be operating blast superheating systems based on the plasma torch, electric resistance and the pebble heat exchanger.

Using plasma torches (Fig 19) to heat cupola combustion air to a temperature of 700 – 800°C has been investigated for both direct firing and blast superheating situations. The principal aim of the process is to achieve satisfactory recarburisation with high steel charges. While plasma technology is well established for use where very high temperature heat sources are required, large plasma torches require a substantial electrical power input and proper control equipment. Furthermore, specialised engineering design techniques must be applied to the torch components and housings if reliability and efficiency are to be achieved.

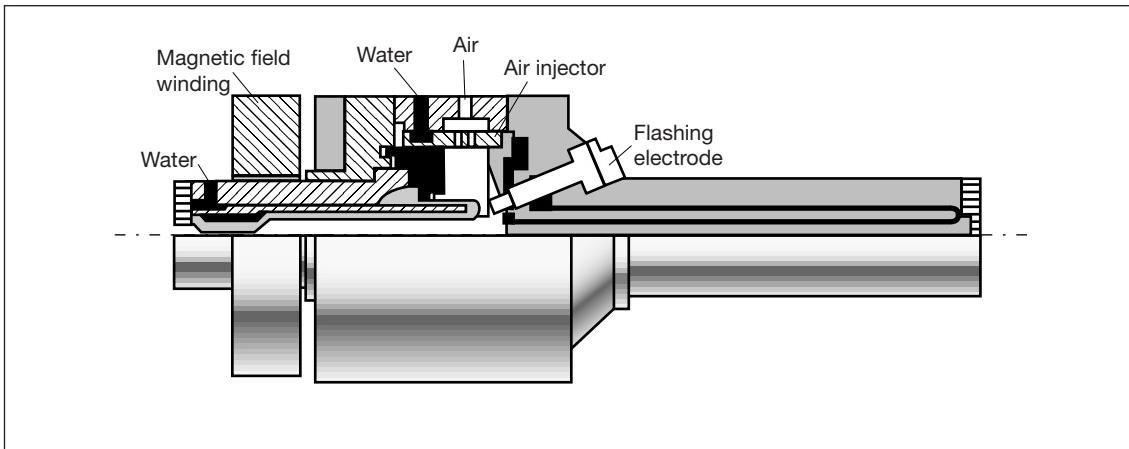


Fig 19 The plasma torch

A French foundry superheats the recuperative hot blast to 700°C using a heat exchange system based on a series of tubes heated internally by electrical resistance elements. This system is simpler and more easily maintained than the plasma system.

In neither the plasma torch nor the electrical resistance case have the heat transfer and overall thermal efficiencies of the system been fully established.

A German foundry superheats the combustion air to a temperature of about 750°C using ceramic pebbles. These are heated by combustion of the cupola top gases and are then recirculated through a heat exchanger section in which the heat is transferred to the cupola blast air.

A possible advantage of blast superheating systems is that foundries may be able to modify their existing cupolas to exploit the technologies identified. However, the heat transfer and overall thermal efficiencies of technologies such as the plasma torch and electrical resistance systems have not yet been fully established. Furthermore, the economics of the various novel techniques need to be established in a range of foundry operations. It is possible that well proven hot blast/oxygen injection techniques may achieve the results required without recourse to these more costly techniques with less well established operating costs. No UK iron founder is known to be operating cupolas using hot blast temperatures above 550 – 600°C. Furthermore, all existing hot blast plants use conventional blast heaters.

8. SAFETY CONSIDERATIONS

Industrial accidents and damage to plant and equipment are both time- and energy-consuming. There are several important safety aspects associated with cupola operation, and failure to observe these can result in explosion, asphyxiation and even loss of life. Reference is made below to seven specific issues which must be addressed.

8.1 Risks Associated with Carbon Monoxide

There have been serious accidents, some fatal, caused by exposure to carbon monoxide. A cupola shell is not gas-tight. It contains gases that are both CO-rich and under pressure. Leaks may occur from bottom doors, breast plate, tapping box, etc.

Operators should take the following precautions to reduce the potential risk:

- maintain adequate ventilation in cupola working area;
- ensure correct arrester design;
- employ mechanical charging where possible;
- ventilate arrester settling tank and/or use high level open trough;
- use leak-proof valves to isolate a non-working cupola from one that is operational;
- introduce safe working practices where operators may be at risk.

8.2 Explosion Risks

The ingress of CO-rich gases into the windbelt or blast main during blast-off periods can cause explosions. To prevent this happening, it is vital that, immediately the blast is turned off, the tuyère cover plates are opened and the valves on the tuyère downcomer or elbow, if fitted, should be closed (Fig 20).

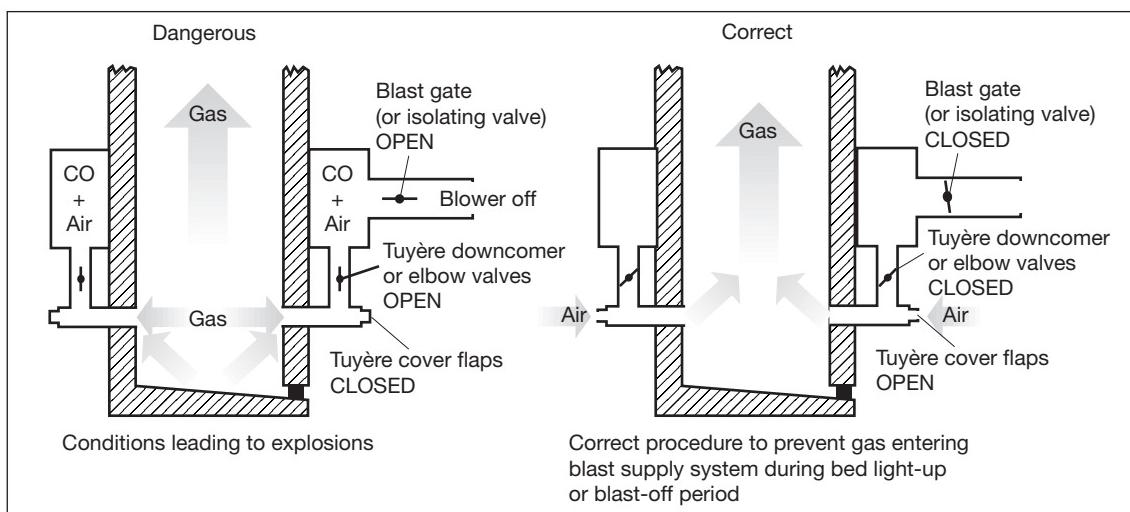


Fig 20 Reducing explosion risks during blast-off periods

The most common types of explosion occur when the cupola bottom is dropped onto lying water. Similarly, the area in which slag pots are emptied should be clear of water.

In liningless cupola operation, either a refractory-lined safety tuyère or a spout should be fitted to act as a by-pass for molten iron, which could otherwise break through the shell and cause an explosion on entering the water trough.

Operators should take the following precautions to minimise the risk of explosions:

- introduce safe operating procedures for cupola shut-down and start-up periods;
- fit explosion-relief systems and/or purge fans;
- on divided blast cupolas, ensure that the separate fans are interconnected;
- keep the cupola drop zone free of water;
- slope the floors below cupolas to facilitate drainage;
- fit a safety tuyère where water cooling is used.

8.3 Securing Cupola Drop-bottom Doors

For safety purposes, the bottom doors of all cupolas should be supported by a robust prop, irrespective of whether or not a door-locking mechanism is used. Props need a firm, permanent base to prevent them from slipping. They should not have to depend for their security on wedges and packing pieces.

Hydraulic rams are now a standard feature, particularly on larger cupolas and long-campaign units. Care should be taken to locate the oil storage tank and associated pumps in a fully protected position, minimising the possibility of contact with molten metal or slag.

8.4 The Cupola Drop

Dropping the cupola bottom is an operation that requires care, and the operator responsible should be satisfied that all the metal and slag has first been drained. Before giving the go-ahead for the operation, audible and visual warnings should be given to ensure that people clear the area. The plant itself should be designed to provide protection at the base of the cupola, preventing debris from escaping and injuring personnel in the vicinity. The floor should be maintained in good condition and, ideally, sloped.

Bottom doors that have stuck can usually be freed by hammering on the staging or by levering them from a safe position. Where such action is not successful, it may be possible to remove the hinge pin securing the door to the base plate. Before attempting this, the doors should be held by temporary supports, and steel sheeting should be provided to protect the operators.

8.5 Fettling the Cupola

The two main hazards facing an operator carrying out cupola lining repairs are:

- materials being accidentally dropped through the charge hole;
- material falling from the cupola wall.

The former can be prevented by locking the door to the charge hole and, in the case of a cupola charging system using a breeches chute, by locking the flap in the appropriate position. The provision of a strongly constructed screen over the operator will prevent injury if materials fall from the cupola wall.

8.6 Oxygen Use

The use of oxygen to improve melting efficiency is commonplace and, although the system is usually fitted with safety interlocking systems based on cupola selection and windbelt pressures, these systems need to be properly maintained to prevent leakage and the possibility of over-exposure in confined areas, and to minimise the explosion risk. External oxygen supplies for lancing should be fitted with a device to prevent accidental usage, together with anti-flash protection valves at the lance connection.

8.7 Charging Systems

Both twin cupola operation with independent charging and single systems servicing two cupolas should be provided with full interlocking safety measures to prevent accidents while repair work is being carried out in the non-operational cupola. Complete electrical isolation is recommended for independent single systems.

9. MINIMISING COKE CONSUMPTION: AN ACTION CHECKLIST

There is considerable scope for cupola operators to reduce their coke consumption by paying careful attention to operating details. The following checklist will help foundries seeking to improve their cupola operation.

1. Avoid intermittent or reduced blast rate operation. Minimum coke consumption is obtained when the blast is applied continuously to the cupola at a measured and controlled rate.
2. Match the melting rate of the cupola to the molten metal requirements of the foundry. Extra coke is used during blast-off and low blast rate periods to reduce the cupola melting rate and maintain the metal temperature. To minimise coke consumption, adjust the diameter of the melting zone so that the cupola can be blown continuously at the optimum blast rate.
3. Measure the coke bed height accurately. An excessive bed height increases coke consumption unnecessarily. Ensure adequate supervision when the bed is being prepared.
4. Repair the cupola lining in the melting zone to retain the original zone diameter. This will reduce coke wastage during bed preparation.
5. Do not light the coke bed too long before the start of the melt. Some foundries light the bed at around 10 p.m. for a 7 a.m. start the next day. As a result, much of the coke burns away uselessly overnight.
6. Avoid holding cupola temperatures for several hours between short morning and afternoon melting campaigns. Better organisation of mould production can shorten or eliminate holding periods and reduce coke consumption.
7. Consider a regime with longer melts on alternate days. Short daily melts mean that the coke bed represents a high percentage of total coke usage.
8. Weigh the amount of charge coke used and maintain the weighing equipment regularly.
9. Keep the charge level as close to the charging door sill as possible to obtain maximum pre-heating in the cupola shaft.
10. Consider the possibility of reducing or eliminating the last one or two charges at the end of the melt.
11. Recover any re-usable coke from the cupola drop at the end of the melt.
12. Ensure that the cupola well is not too deep. It must be deep enough to ensure adequate carbon pick-up and good mixing of the molten iron, and to hold all the slag produced between slag removal operations, but wells that are too deep reduce metal temperature.
13. Make sure that average coke size complies with the recommendations. Small-size coke (less than 50 mm) burns less efficiently than large coke and so larger quantities are required to obtain a desired metal temperature. Prevent coke breakage by minimising the number of separate handling operations involved in delivering it to the cupola. Design storage facilities and lifting and transfer mechanisms to minimise size degradation.

14. Check metal temperatures. If the metal produced has to be cooled before pouring to prevent defects due to sink, draw and internal shrinkage, energy is being wasted. Alternatively, if the metal distribution system allows excessive temperature loss between furnace tapping and mould pouring, castings will have to be scrapped because of cold-metal defects such as mis-runs, blows and laps.
15. Weigh the flux addition to obtain effective control of slag formation. Consistently smooth cupola operation depends on the flux addition being correct.
16. Only consider water-cooled, liningless operation on large diameter (more than about 950 mm) hot blast cupolas. A considerable amount of heat can be lost through the shell of water-cooled liningless cupolas.
17. Consider converting cold blast cupolas that operate with melting periods of more than four hours to divided blast operation. The conversion of cupolas with a short stack (less than about 4.5 m) should be examined with caution because of the loss of pre-heating associated with a higher coke bed.
18. Consider the continuous injection of oxygen into the cupola blast. This will allow a reduction in charge coke with no loss of metal temperature. Using oxygen to obtain hot metal quickly at the start of a melt or following a shut-down can also save energy by eliminating the need to pig metal and perhaps reducing the scrap associated with cold metal defects.
19. For foundries wishing to maintain a continuously high melting rate, a single hot blast cupola using a recuperator for blast pre-heating on a long campaign basis offers the best opportunity for minimising coke consumption.

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New Practice: monitors first commercial applications of new energy efficiency measures.

Future Practice: reports on joint R & D ventures into new energy efficiency measures.

General Information: describes concepts and approaches yet to be fully established as good practice.

Fuel Efficiency Booklets: give detailed information on specific technologies and techniques.

Energy Efficiency in Buildings: helps new energy managers understand the use and costs of heating, lighting etc.